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Title: From DUFF to KRUSTY - The Path to Successful Reactor Development

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From DUFF to KRUSTY - The Path to Successful Reactor Development

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Orgs: NASA, NNSA, GRC, MSFC, LANL, Y-12, NSTec, SunPower, Materion

40+ Years of Reactor Stagnation

- **Space fission power programs have been ongoing (at various levels) since the 1950s, but to date the US has flown only one space fission system, SNAP-10A, in 1965.**
  – SP-100 and JIMO accounted for well over $1B with no significant progress.
    - Programs did not come remotely close to testing a prototype.
    - Countless of other space reactor programs have resulted only in paper.
  – Things are even worse for terrestrial reactors.
    - Since its formation in 1977, the DOE has spent several billion dollars on advanced reactors technologies and concepts, with nothing significant to show for it.
- **Why have these previous programs failed?**
  – Programs lost support because they became too expensive and/or dragged on with insufficient progress.
    - Public and political bias against nuclear have not played a major role – i.e. we continue to launch Pu-238.
    - Regulation has not been a “first-order” factor in preventing progress on the government side either.

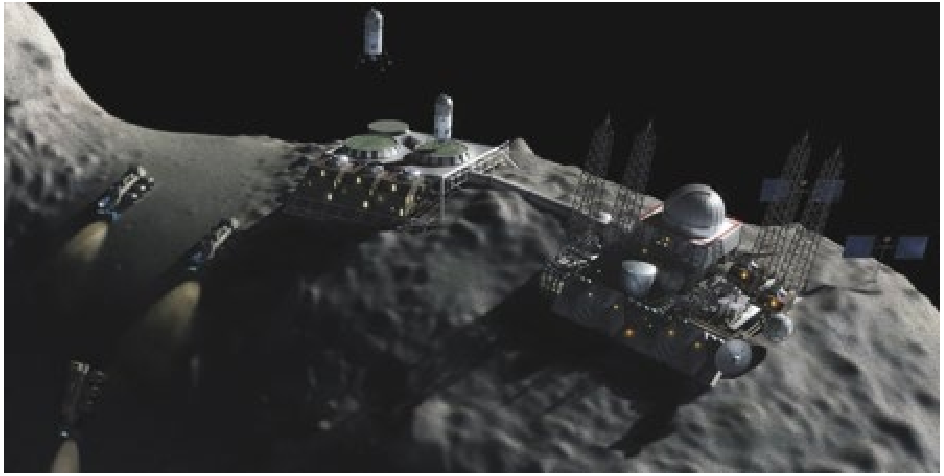
SNAP-10A

Why have programs failed to make progress? – Our Opinion.

- **Too large of a first-step**
  - Over-sold paper concepts – there's always someone that claims they can provide a higher-performance system to woo a customer.
    - Usually a concept is pursued with marginally better performance but a substantially harder development risk.
  - Need a path to a successful system demonstration within a few years (or every few years depending on how many steps are needed).
    - Then, eventually arrive at higher performance systems through evolution.
- **Programmatics – everyone is at fault (my personal opinion of course)**
  - Congress: White collar welfare – congress has Centers/Labs/Large Corporations to feed.
  - Decision makers: Risk aversion; i.e. decision makers seem to prefer "safe" studies to figure out what to do, than risk actually doing anything in fear of potentially making a bad choice.
    - This results in more planning and paper studies
  - Bureaucrats: Who the money goes through, and making them feel good, matters more than progress.
  - Labs/Corporations: Follow the cash, no push back on unreasonable requirements/expectations.
  - Engineers: Eager to try solve tough problems, instead of recommending more pragmatic solutions.

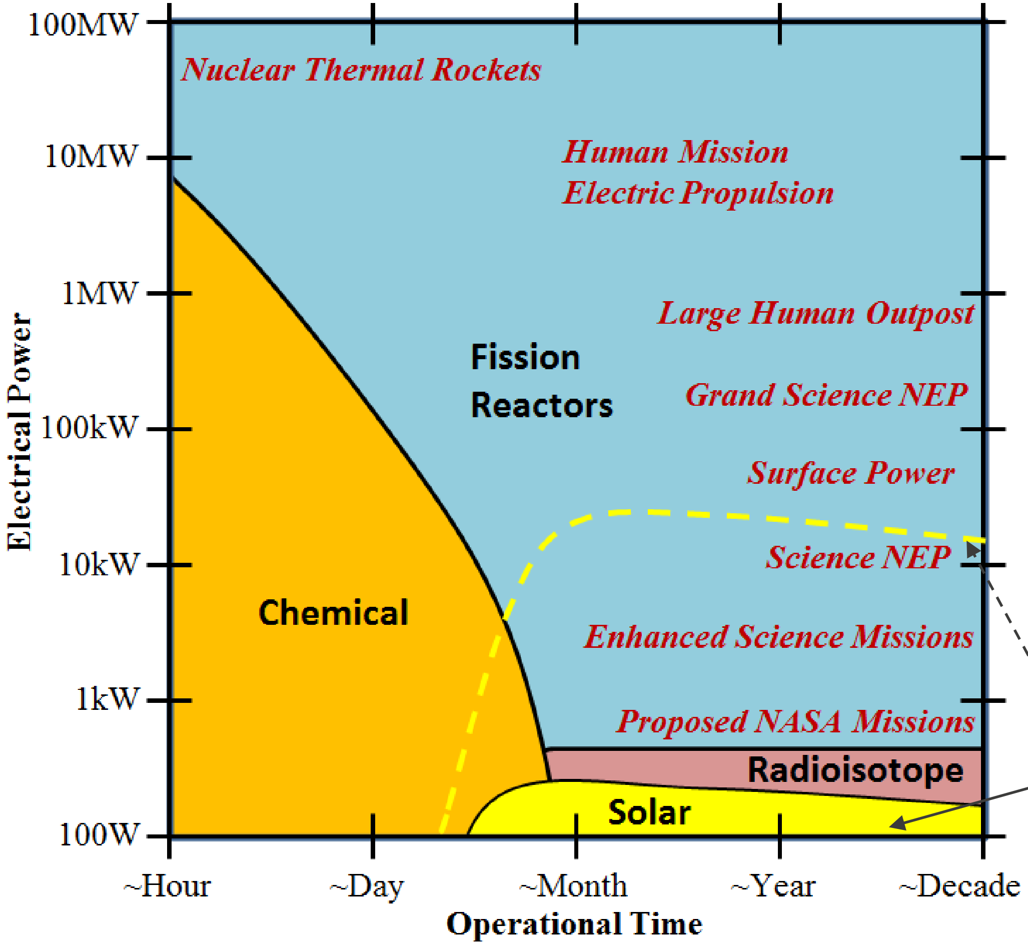
Why Space Reactors?
Potential Applications of Space Fission Power

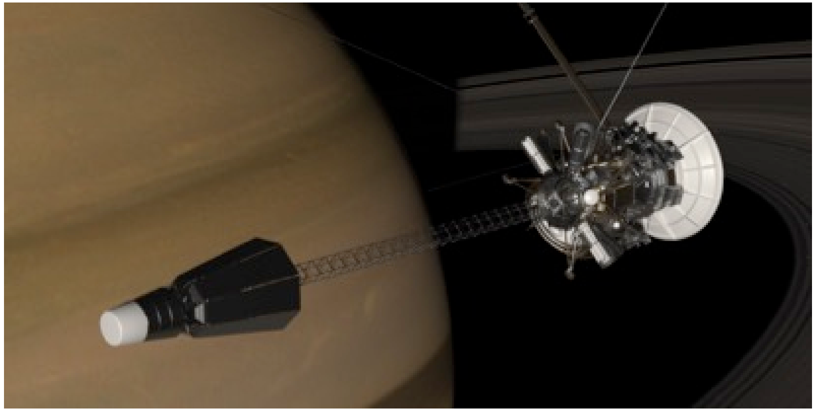
- **NASA Missions**
  - Human Mars surface missions
  - Lunar (moon) surface missions
  - Deep Space Science
  - NEP planetary orbiters and landers:
    - Europa, Titan, Enceladus, Neptune, etc.
  - Asteroid exploration and deflection



- **Commercial Missions**
  - Space power utility
  - Asteroid/space mining
  - Lunar/Mars settlements
- **Power uses**
  - drilling, melting, heating, oxygen/propellant production, refrigeration, sample collection, material processing, manufacturing, video, radar, laser, electric propulsion, telecomm, rover recharging
- **Defense Missions**
  - Fission power might play a role in a potential space race
- **Simple evolution of Kilopower to higher power reactors (>1 MW)**
  - Electric propulsion for large cargo or human missions
  - Surface power for larger lunar or Martian settlements.
  - "Microreactors" for use on the Earth

Potential NASA Power Sources





This chart includes very rough estimates of mass, practicality and utility of each power source.

The utility of solar power is obviously dependent on distance from sun and/or possibility of day-night cycle.

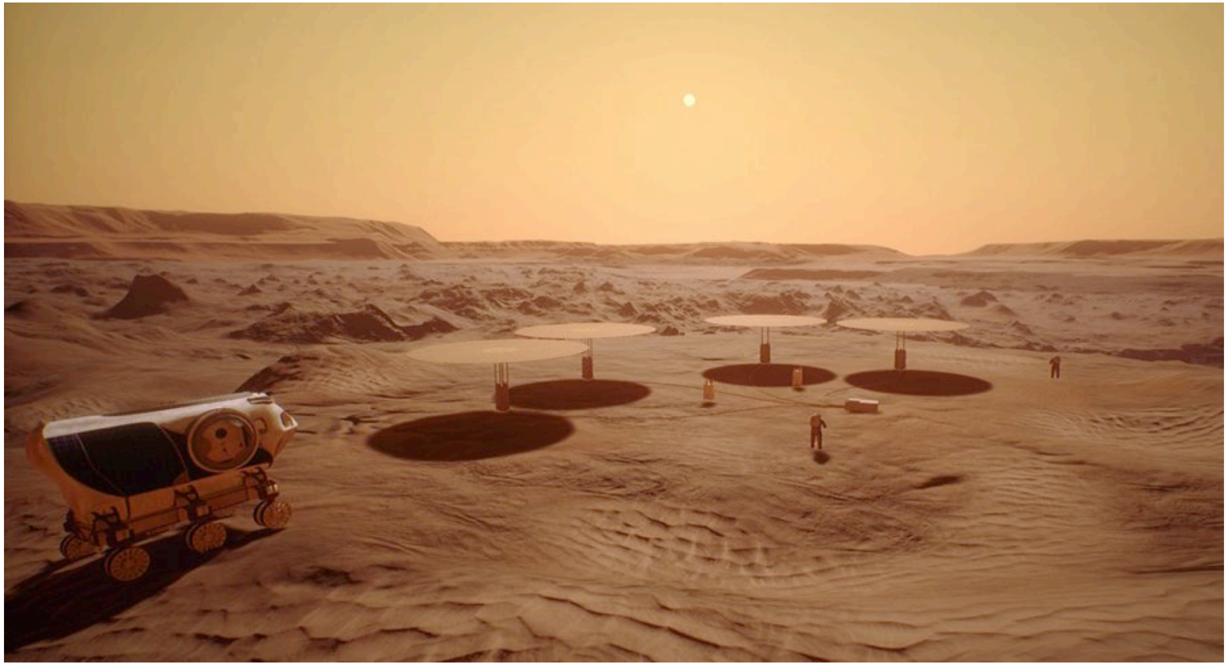
Yellow curve is estimate of utility at 10 AU, dotted yellow line is estimate at 1 AU (for no eclipse application). Mars curve would be highly mission dependent.

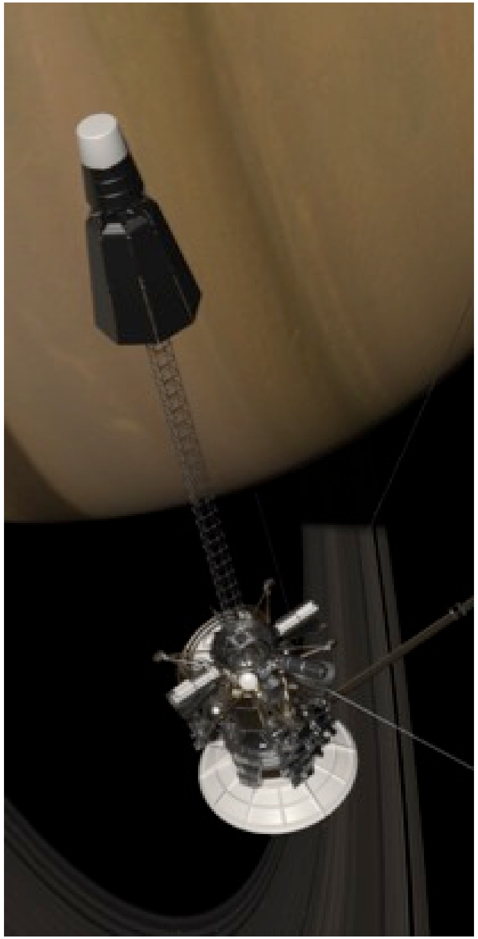
Space Reactor Launch Safety

- **A reactor that has not undergone fission, (been turned on), has very very low safety concerns. It will have from 1 to 10's of curies of naturally occurring radioactivity**
- **This is 1,000s to 10,000s times lower radioactivity than in current radioisotope systems already flown in space**
- **Full dispersal launch accidents would have consequences <u>100's of times less</u> than background radiation or radiation from a commercial plane flight**
- **After the reactor has fissioned, it will become radioactive**
  - Reactors would only be used in deep space, very high Earth orbit (long term decay) and on other planets.
  - Kilopower reactors are designed to stay subcritical in all accident conditions (water, sand, fire, etc.) – the only way the reactor can generate power is if the radial reflector is intact and the B4C rod is withdrawn.

Kilopower Reactors

- Reactor concepts produce from 1 to 10 kWe at low mass, or up to 25 kWe for an LEU system.
- Reactor easily adapted to operate in space or on surface, and for robotic or human missions – power system accommodates modular shielding blocks
- The reactor technology/approach evolves up to > 1 MWe without significant change/risk from a nuclear perspective.



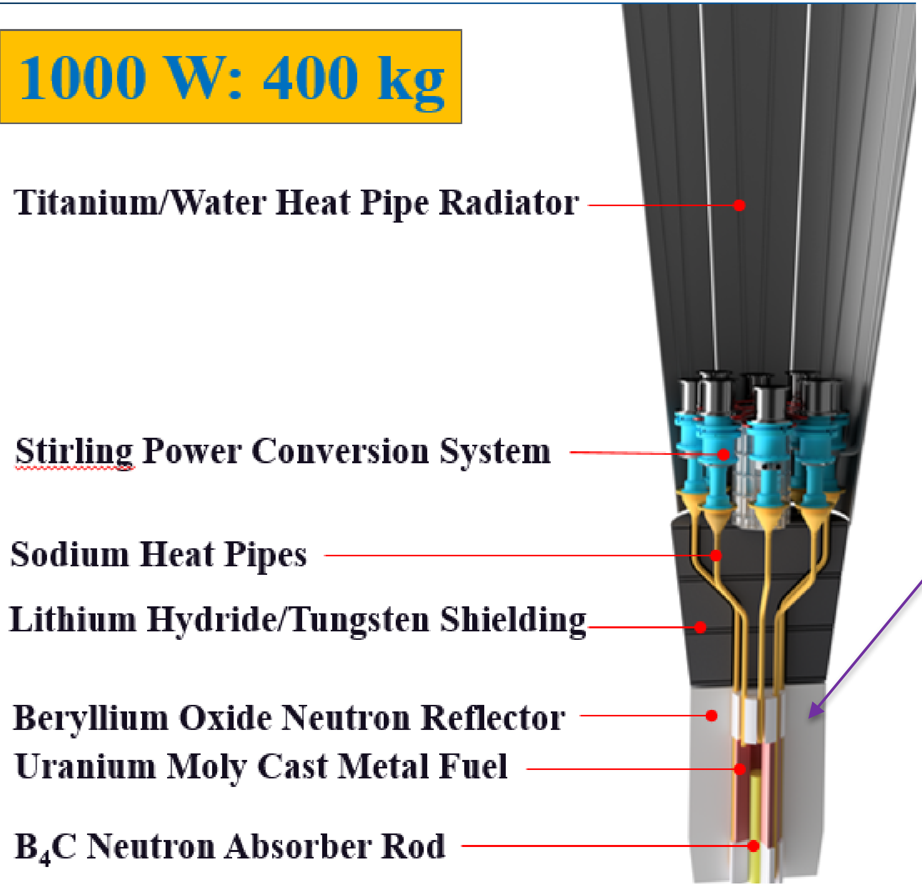


Kilopower 1-kWe Space Concept

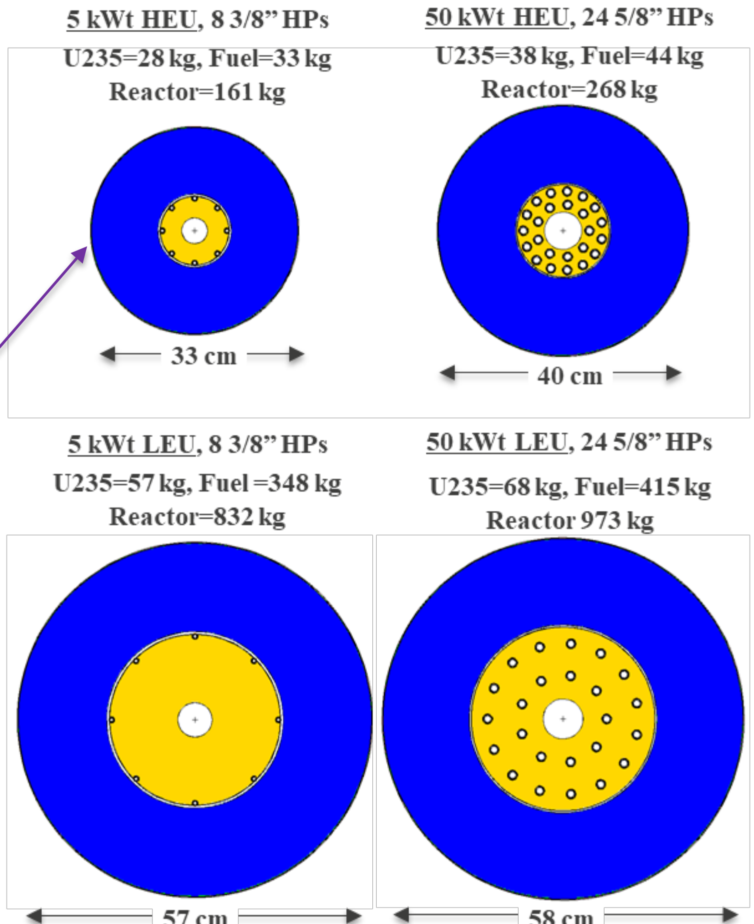
KRUSTY

Fission Power to Enable Space Exploration

1000 W: 400 kg



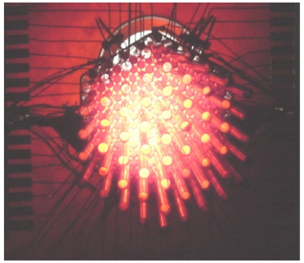
KRUSTY is prototype of this concept

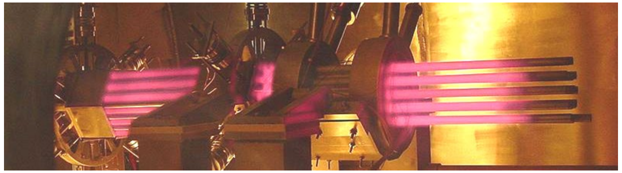


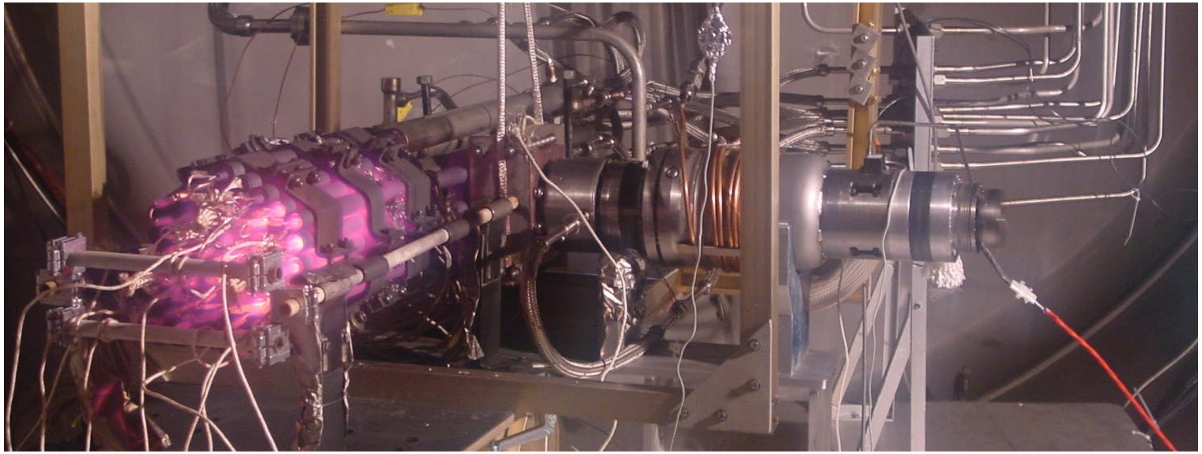
How Did We Arrive at Kilopower, DUFF and KRUSTY?

KRUSTY
Fission Power to Enable Space Exploration

- **We wanted to find a space reactor concept that could be…**
  - 1) Attractive to NASA for flight
  - 2) Proven with a rapid turnaround, low-cost nuclear test.
- **Past work (HOMER/SAFE) convinced us that heat-pipe-cooled reactors provide easiest path to near-term, low-cost concept.**
  - Simple, passive reactor operation, high reliability, ease of testing
  - Stirling engines allow simplest reactor (low thermal pow, simpler reactor control)







Demonstration Using Flattop Fissions = DUFF
A “Critical” Starting Point

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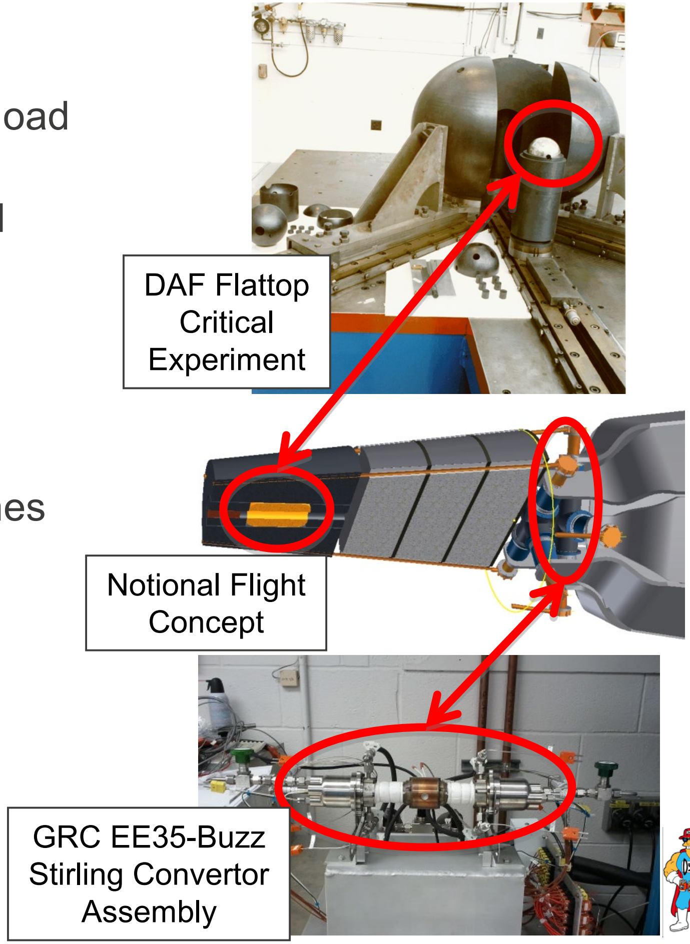
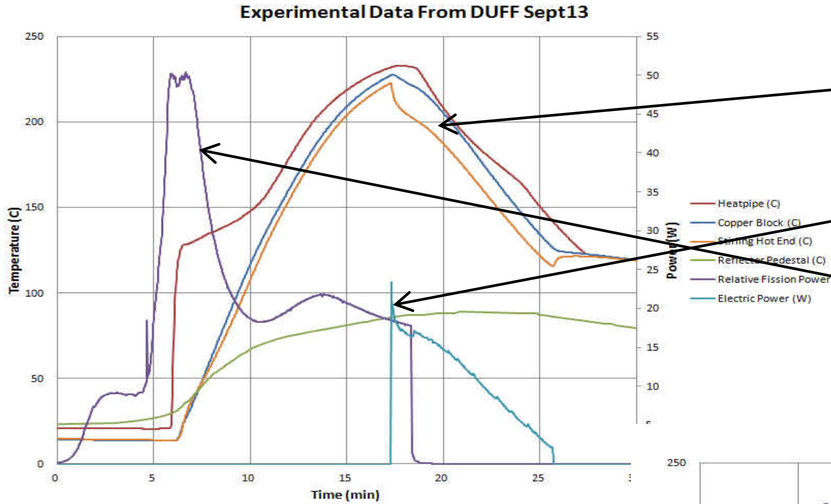
- **Proof-of-Concept Test – Objectives**
  - Use electric power generated from nuclear heat to power a load (light panel)
  - Demonstrate that basic reactor physics is well characterized and predictable using current analytic tools
- **Test Configuration**
  - HEU core with central hole to accommodate heat pipe
  - Heat transfer via single water heat pipe
  - Power generation via two opposed free-piston Stirling Engines
- **Significance**
  - First-ever use of heat-pipe to transfer reactor power.
  - First-ever Stirling engine operation with fission heat
  - Demonstrated nuclear reactivity feedback was predictable
  - Demonstrated that powered nuclear testing is not inherently expensive or time consuming – simplicity is paramount.



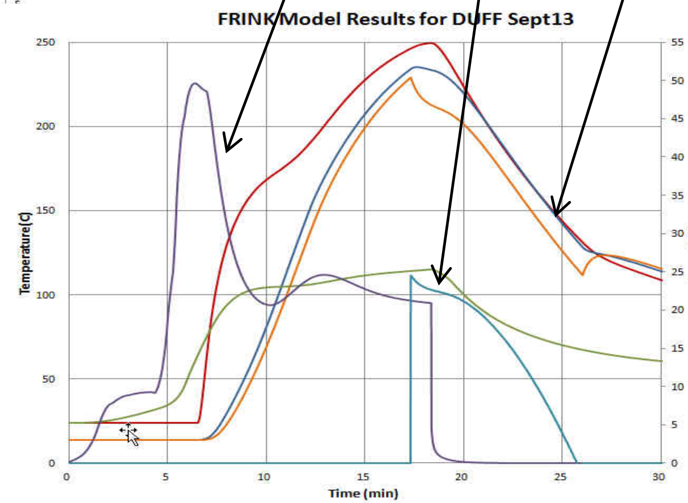
DUFF Sept 13th Results Compared with FRINK System Model

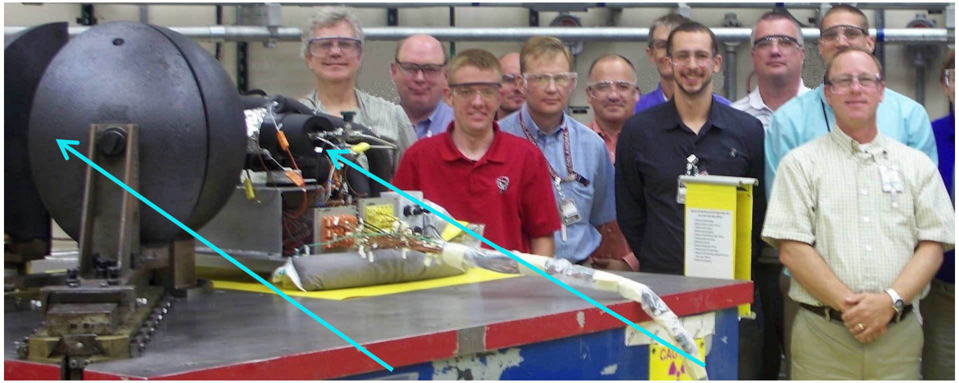


Power Conversion System Temperatures

Electrical Power

Reactor Thermal Power





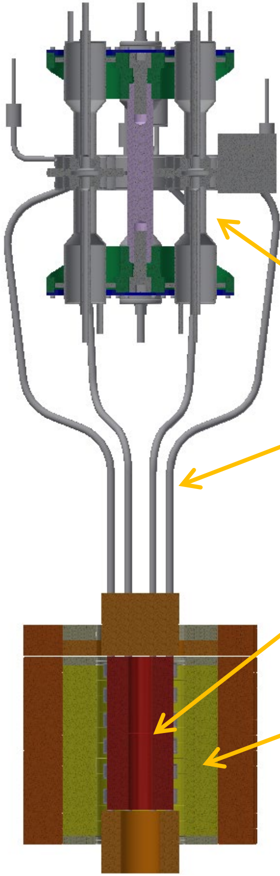
Core and reflector

Stirlings

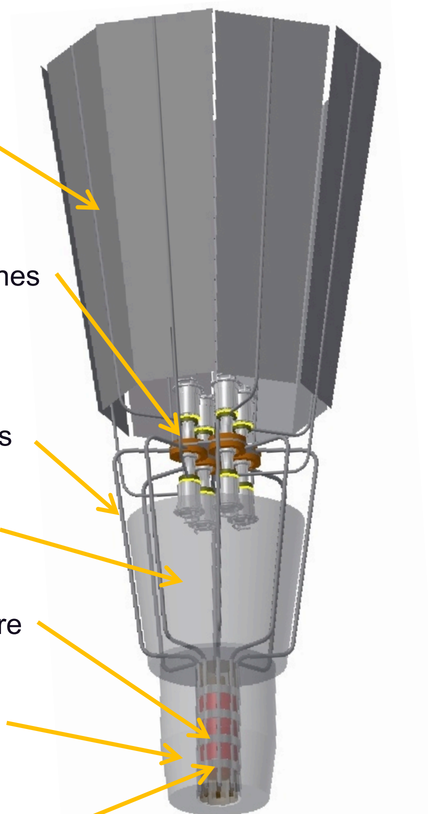
Kilowatt Reactor Using Stirling TechnologY
KRUSTY -- *The Next Step Toward Flight*

KRUSTY

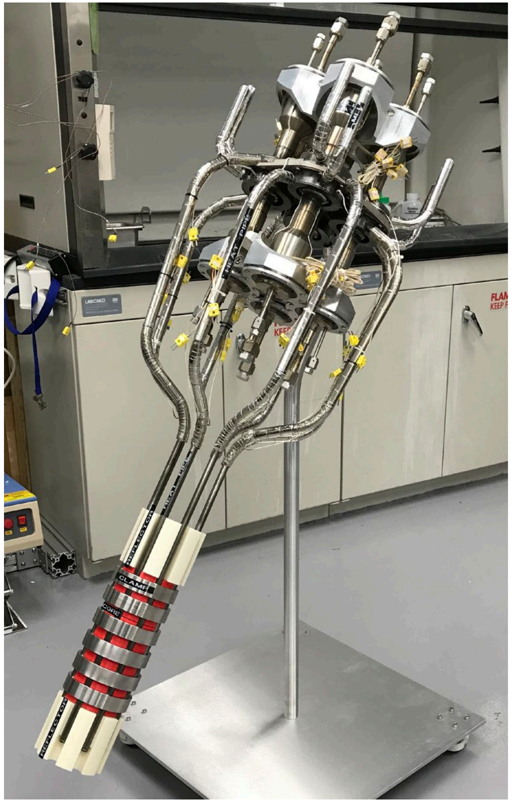
Fission Power to Enable Space Exploration



KRUSTY



Space Flight Concept

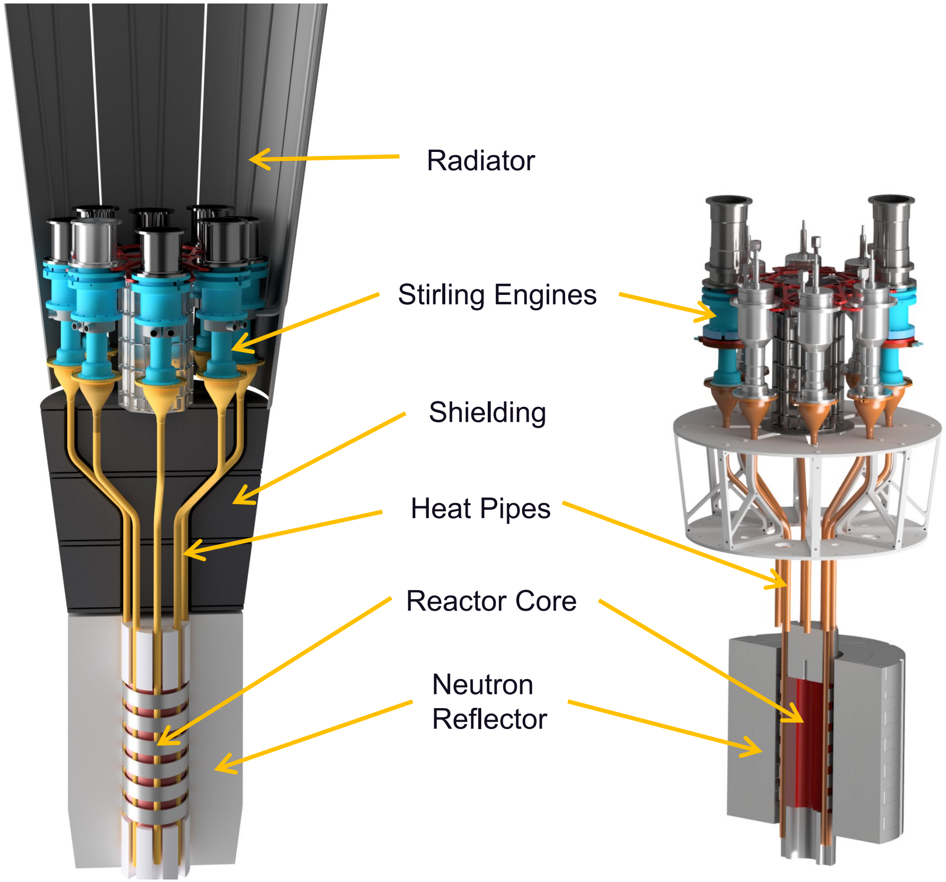


Prototyping Mockup of KRUSTY

Kilowatt Reactor Using Stirling TechnologY
KRUSTY -- *The Next Step Toward Flight*

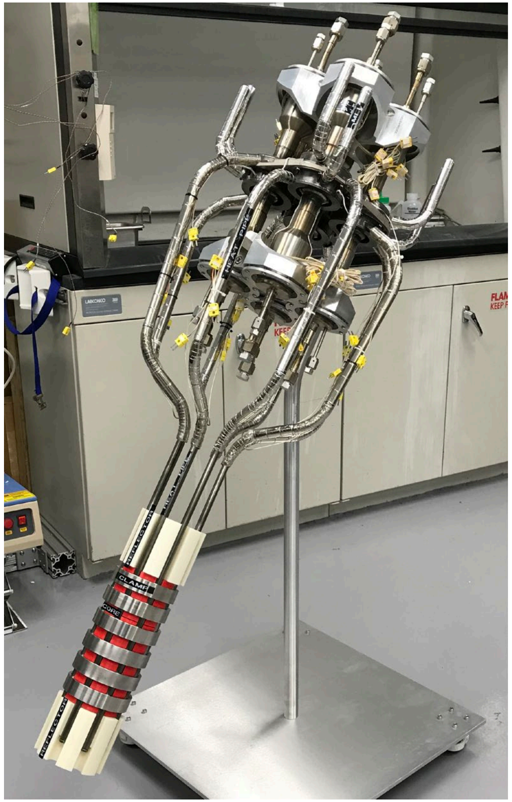
KRUSTY

Fission Power to Enable Space Exploration



Space Flight Concept

KRUSTY



Prototyping Mockup of KRUSTY

Initial goals to make KRUSTY the most valuable and "prototypic"; e.g. for a flight system

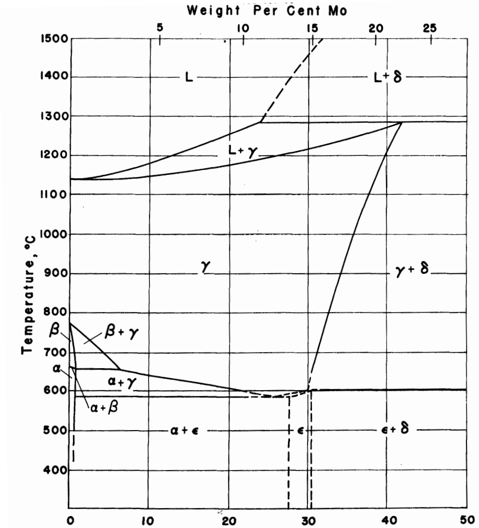
- Thermal/neutronic coupling: dynamics, stability, load-following, heat-pipe cooling, etc.
- Core materials: all materials as close as flight prototypic as possible
- Power: deliver thermal power of similar magnitude and efficiency of flight system.
- Core Temperatures: thermal, structural, material/chemical, neutronic performance
- Reflector material: eliminate neutronic uncertainties with highly reflected beryllium
- Vacuum environment: for heat transfer, but required for materials/temps regardless
- Stirling Integration: demonstrate interfaces and representative dynamic response.
- Core geometry: resemble flight, in particular conduction paths to heat pipes
- Reactor control: considered less important, because if KRUSTY proved us correct, then the flight system doesn't need active reactor control (only simple movements for startup, and if desired, temperature changes), and system-dynamics is validated regardless of reactivity control method.
- Reflector temperatures: Less important because substantially slower time constant.
- Shielding: hard to benchmark shielding characteristics with room/equipment scatter

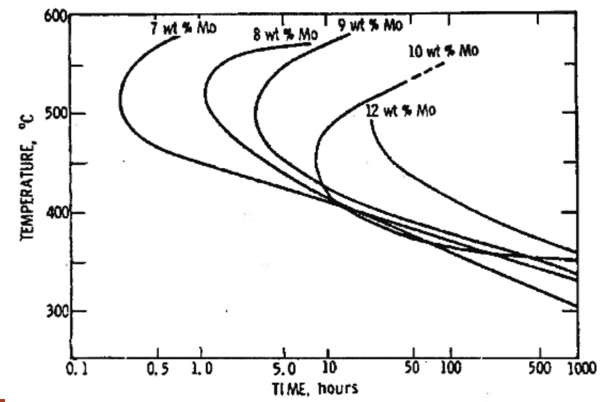
Goal was be as prototypic we could get within a cost/schedule that would appeal to NASA, and prove predictable/robust power system operation. All of the high and mid priority goals were ultimately satisfied.

Why UMo Fuel?

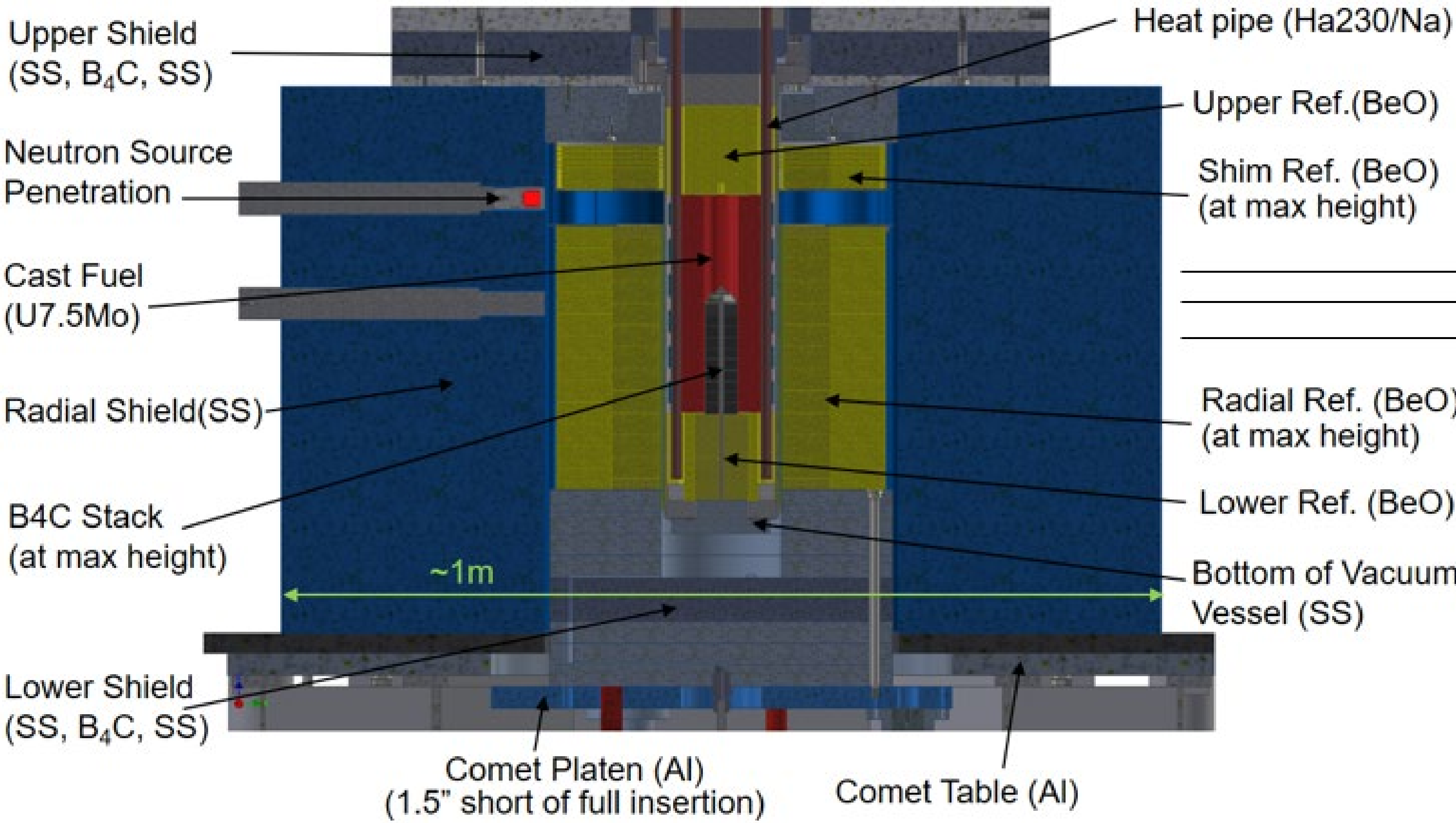
KRUSTY
Fission Power to Enable Space Exploration

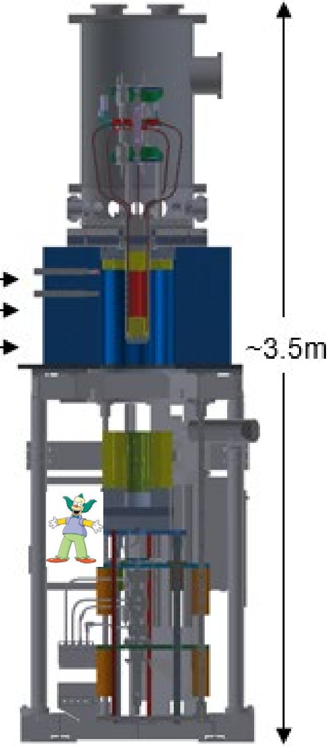
- **Metallic Fuel**
  - High Uranium density
  - High thermal conductivity
  - Ease of fabrication
  - Existing infrastructure
- **Pure uranium would be favorable to Umo neutronically (lower mass) and for ease of casting, but phase changes could be problematic during repeated testing.**
  - It may not be a big deal with limited thermal cycling, and especially space system that only fires up once and stays hot.
- **UMo also has slightly higher strength at elevated temperatures.**
- **INL, Y12 and others continue to increase the U-Mo, U-metal experience and database.**
- **Best reason - Y12 was able to deliver the core!**





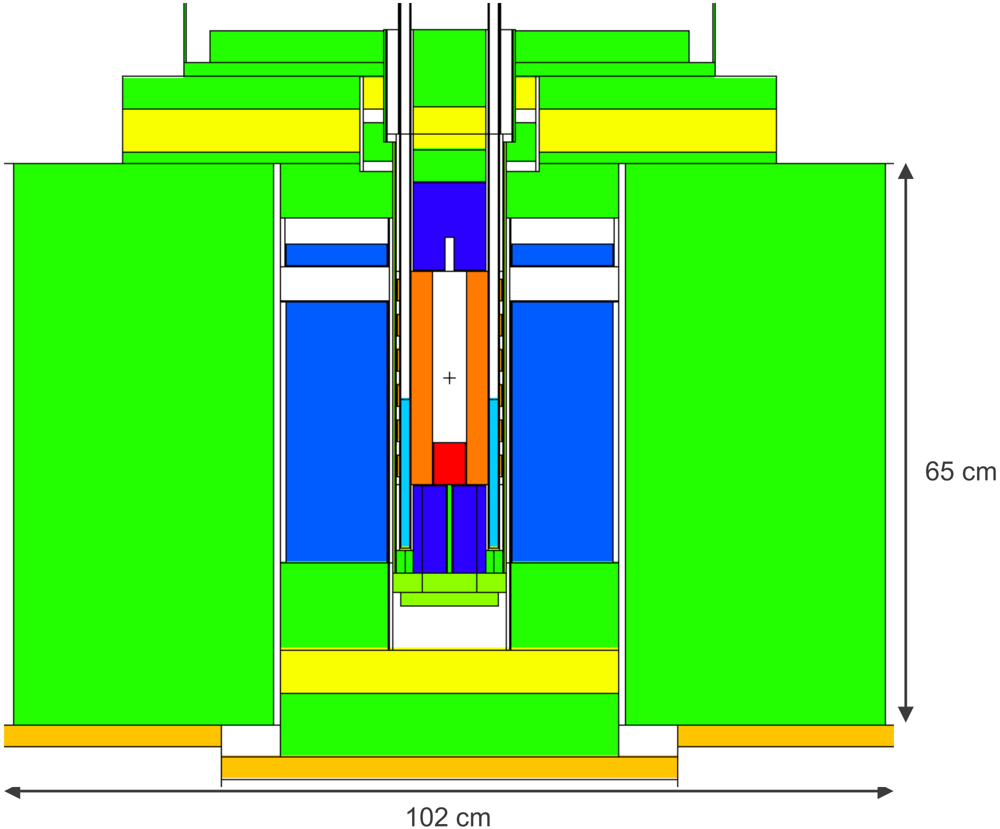
KRUSTY REACTOR CONFIGURATION

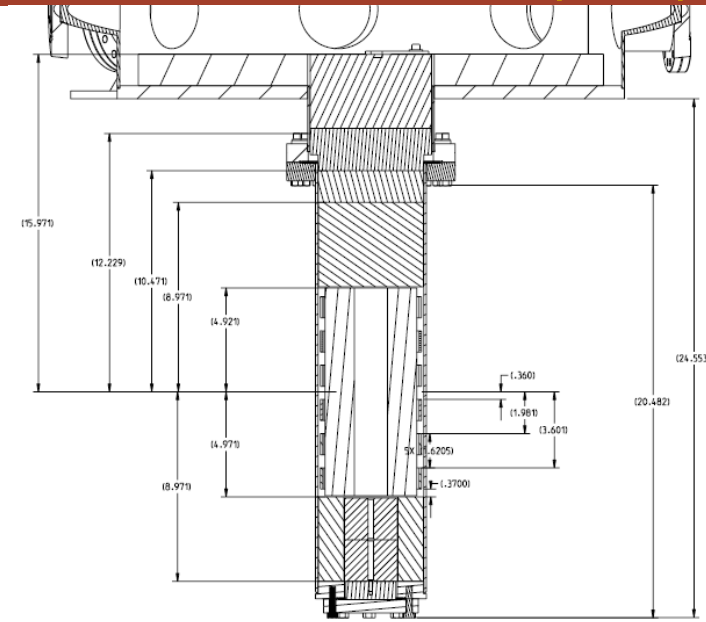




KRUSTY atop Comet
Platen fully withdrawn

KRUSTY MCNP Model

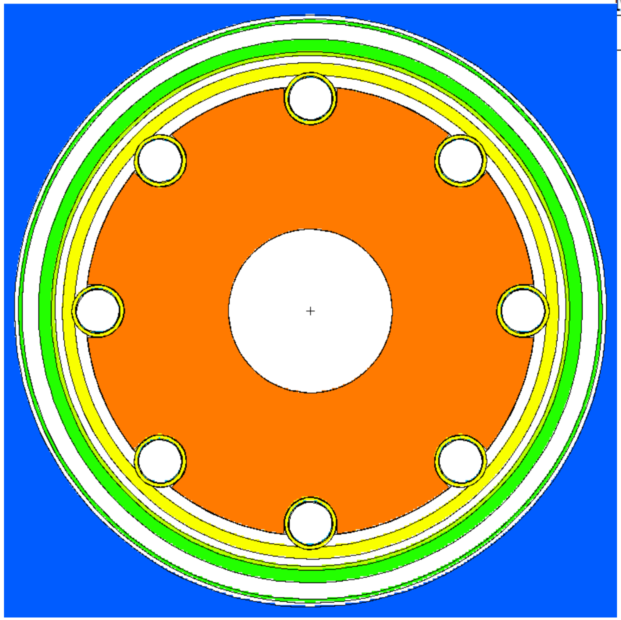




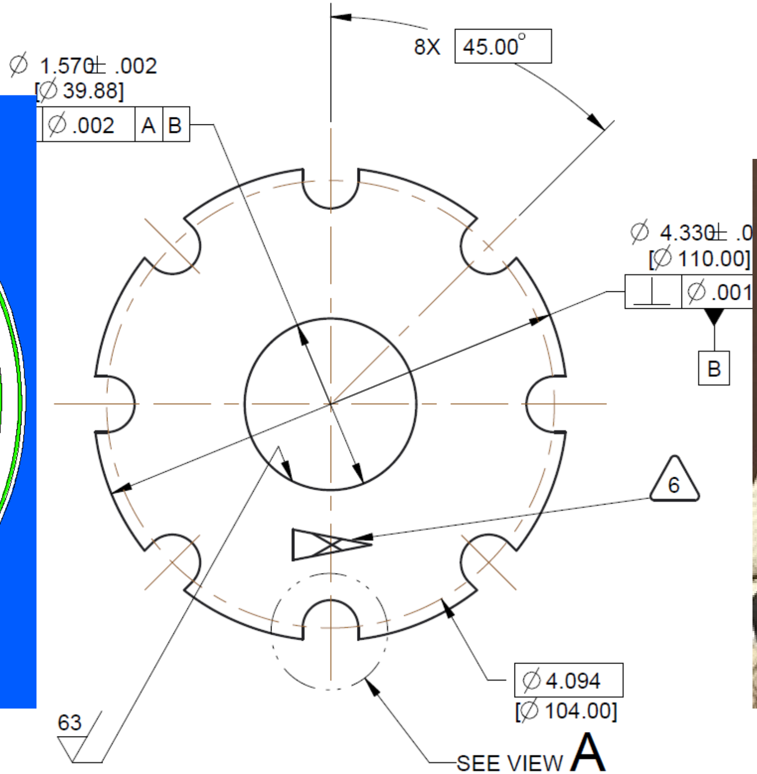
Initial design drawings were literally the MCNP model

Orange	U8Mo
Blue	BeO
Green	SS316
Red	B4Cenr
Yellow	B4C
Light Orange	Al
Light blue	Na

Frequent iterations between model, design-drawings, and fabrication issues



MCNP model



Design Drawing

DU Core Piece

Parts modeled at spec – fuel tolerances +/- 0.002”

KRUSTY Development Path

KRUSTY

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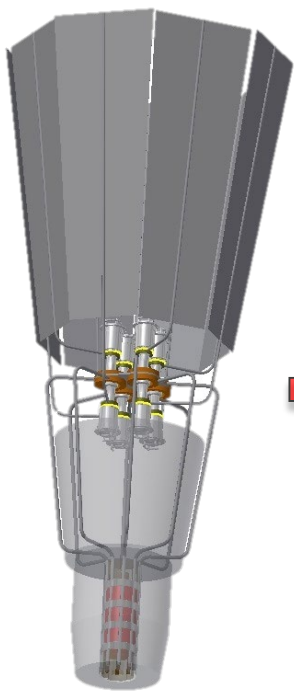
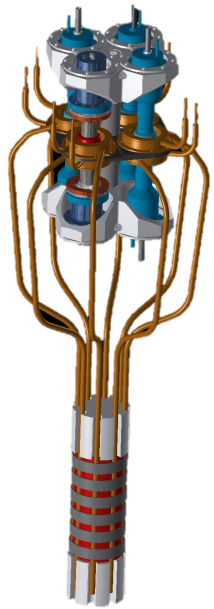
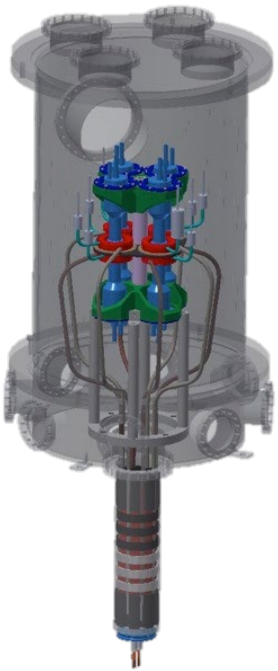


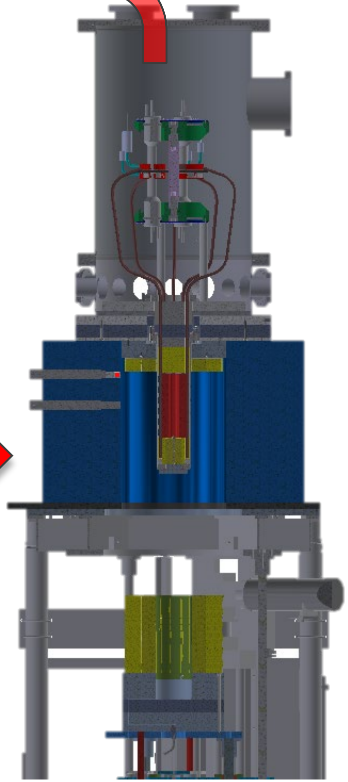
Flight Concept



Flight-prototypic Power Pack



Electrically Heated Test with Depleted Uranium Core



Nuclear-Powered Reactor Demonstration with enriched Uranium Core

KRUSTY: Thermal Prototype

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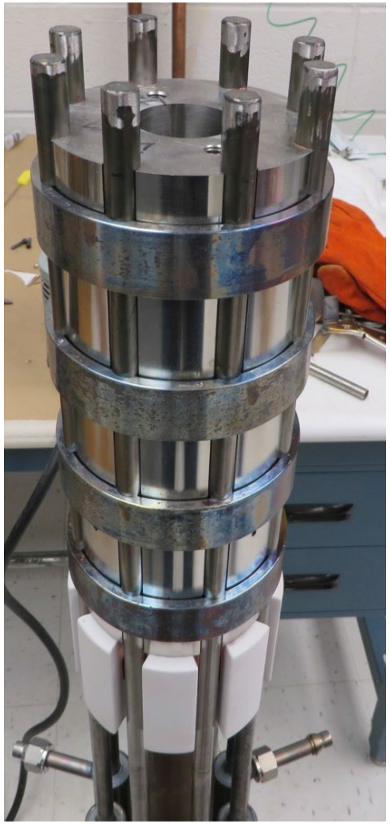
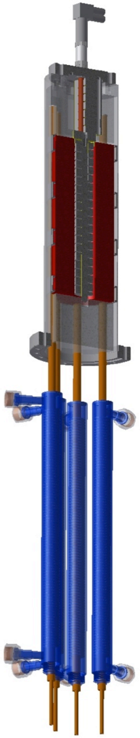
- **Vacuum Test**
  - Stainless Steel Core
  - Electrically Heated
  - Haynes 230/Na thermosyphons
  - MLI insulation
  - Prototypic Core Can

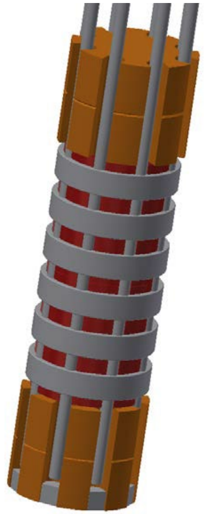
- **Addresses**
  1. 3+ clamp designs
  2. Core can design
  3. Thermal Interfaces
  4. Creep modeling
  5. MLI performance
  6. Assembly process
  7. Electrical heater



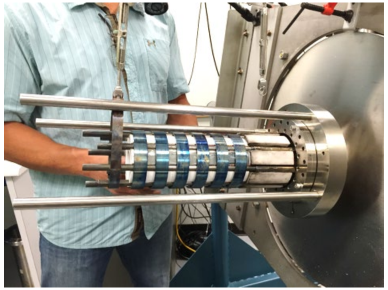


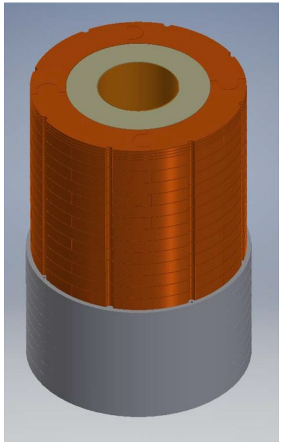
KRUSTY Subsystems

Uranium Core Segments

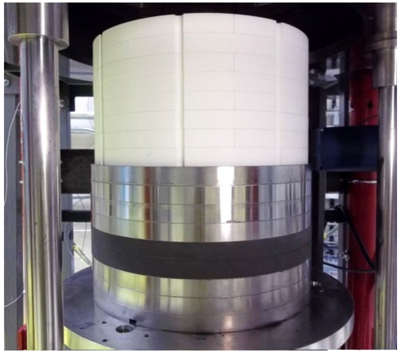


Reactor Assembly

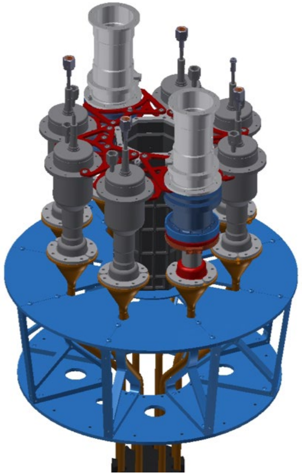




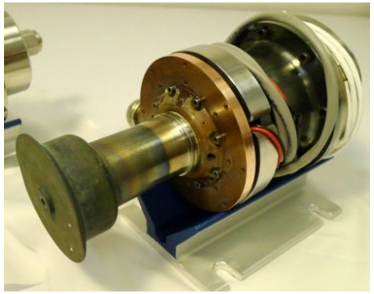
BEO Axial Reflector (Materion) and lower SS/B4C shield



Na/Ni-alloy heat pipes (wick only in evaporator, pool region)



Stirling Engines (Sunpower) & Simulators



Benchmarking with Electrical Testing.

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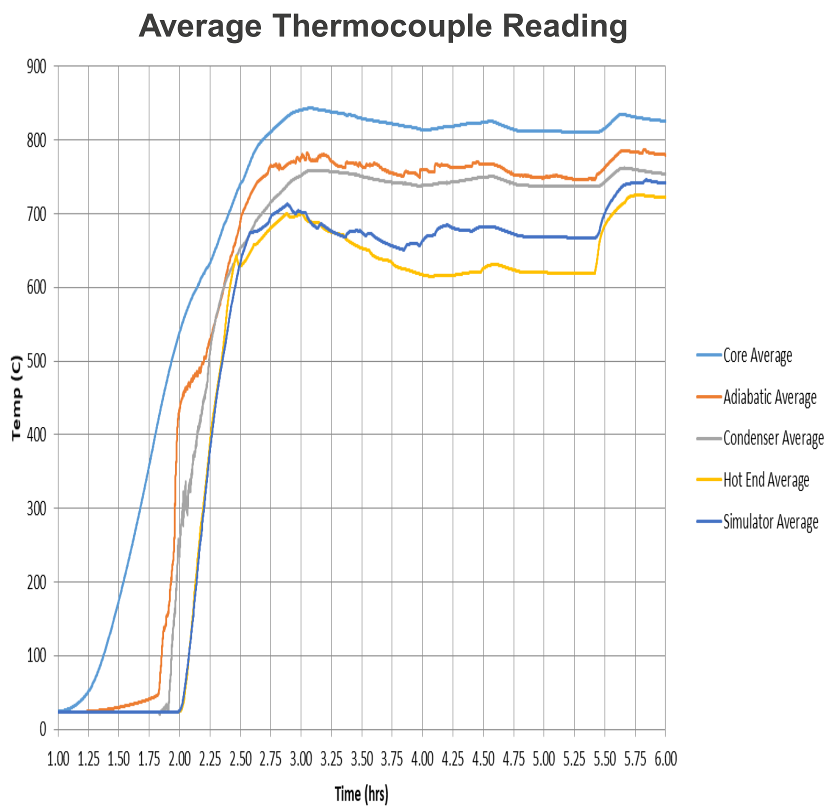
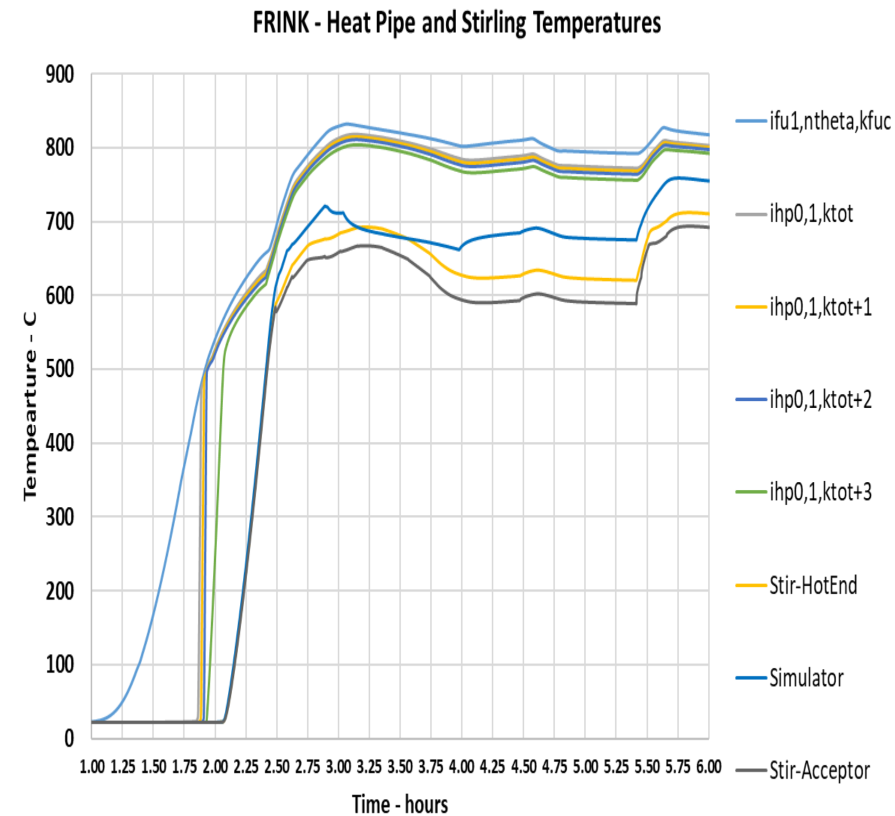
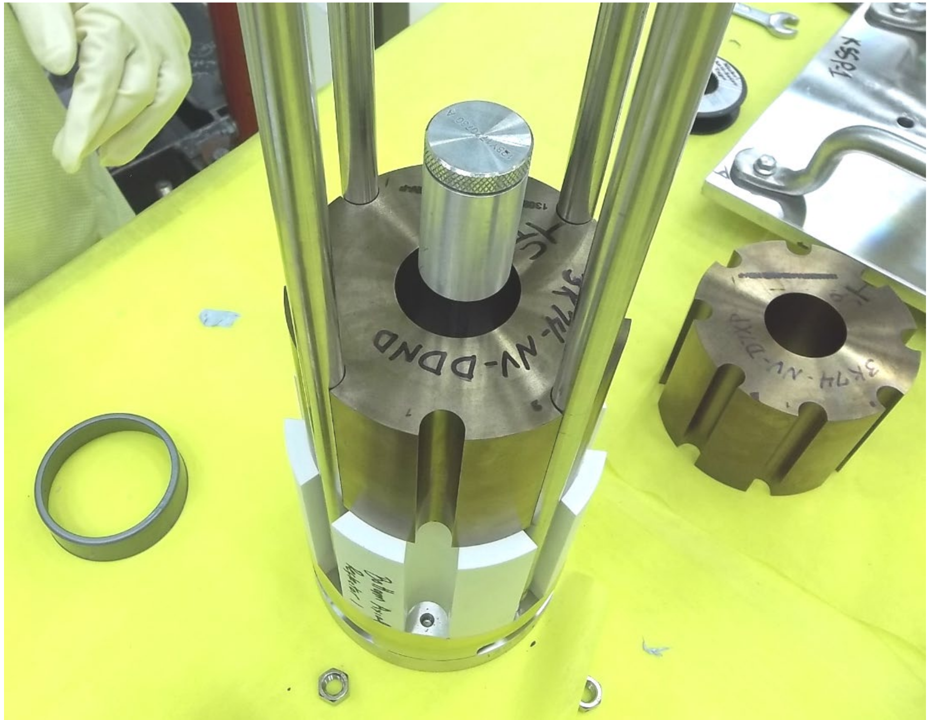


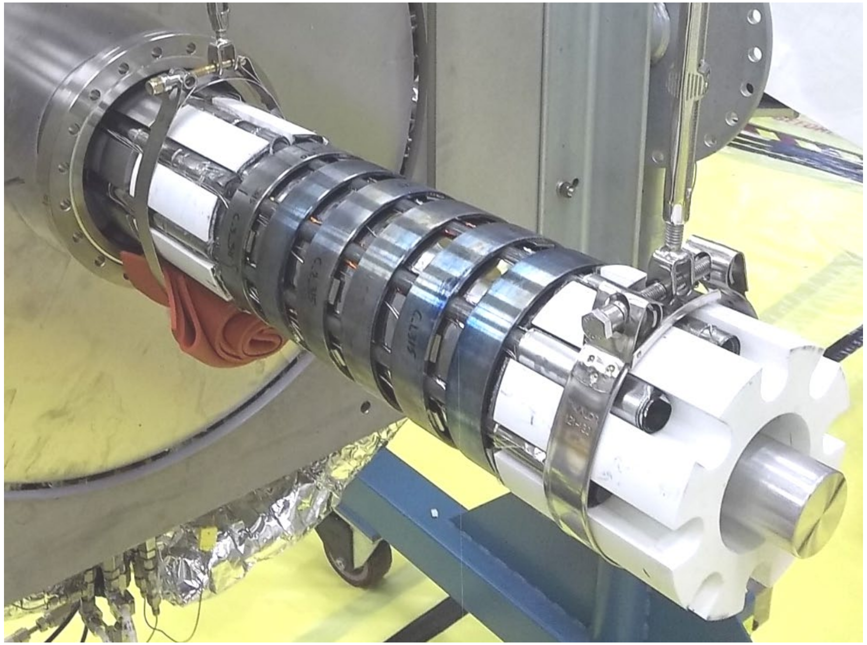


Electrical testing was huge: 1) work out kinks in design, 2) develop instrumentation and control, 3) give regulators confidence in system operation, 4) benchmark the codes that ultimately gained, regulator approval.

KRUSTY Assembly



Partially assembled configuration for the component criticals. The first (of 3) HEU UMo core segments rests on top of the lower BeO axial reflector. The central cylinder aids assembly and alignment, and is later removed.



The assembled KRUSTY reactor core, ready to be enclosed within the vacuum vessel. Six Haynes 230 rings are clamping the Na heat pipes to the HEU UMo core, with white BeO axial reflectors on both ends. A temporary fixture to aid assembly (soon to be removed) protrudes from the bottom and surrounds each reflector. The vacuum flange is on the far left.

Criticality Safety of Core/Assembly

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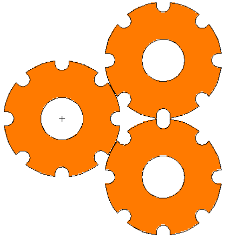
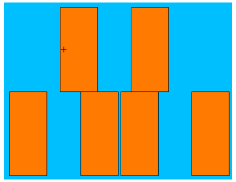
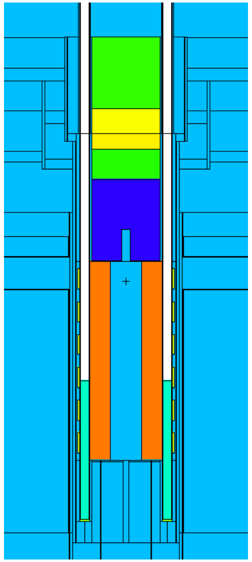
- **Calculations performed to ensure criticality safety during all phases of project: fab, handling, assembly and operations.**
- **Keff calculations are shown below.**

	bare	water	sand	wet-sand
Flattop HEU core ball	0.6576	0.8991	0.8166	0.8863
KRUSTY fuel 1 section	0.4577	0.7642	0.6034	0.7127
KRUSTY fuel 3-section column	0.5886	0.9591	0.8310	0.9346
KRUSTY fuel 3-section triangle pitch	0.5776	0.9710	0.8210	0.9368
KRUSTY fuel 3-section paint-can stack	0.5846	0.9806	0.8296	0.9446
KRUSTY assembly outside of vessel/shield	0.6148	0.9155	0.8311	0.9062
Same as above with central void not filled	0.6148	0.8612	0.8277	0.8881

  – "KRUSTY assembly" adds heat pipes, clamps, upper reflector/shielding, mli.







- **There is no material that the fuel could be accidentally surrounded by that would take the fuel critical other than Be or another fissile material**
  – This is by design, because the flight reactor is designed so to remain subcritial during launch accidents (water immersion with worst case wet-sand surround).
    - Academic caveat: a form fitting full (4pi) encasement of >1m thick of high-density/purity graphite could do the trick).

Sample safety calculation: Modeling of $3.00 Uninterrupted Full Reactivity Insertion

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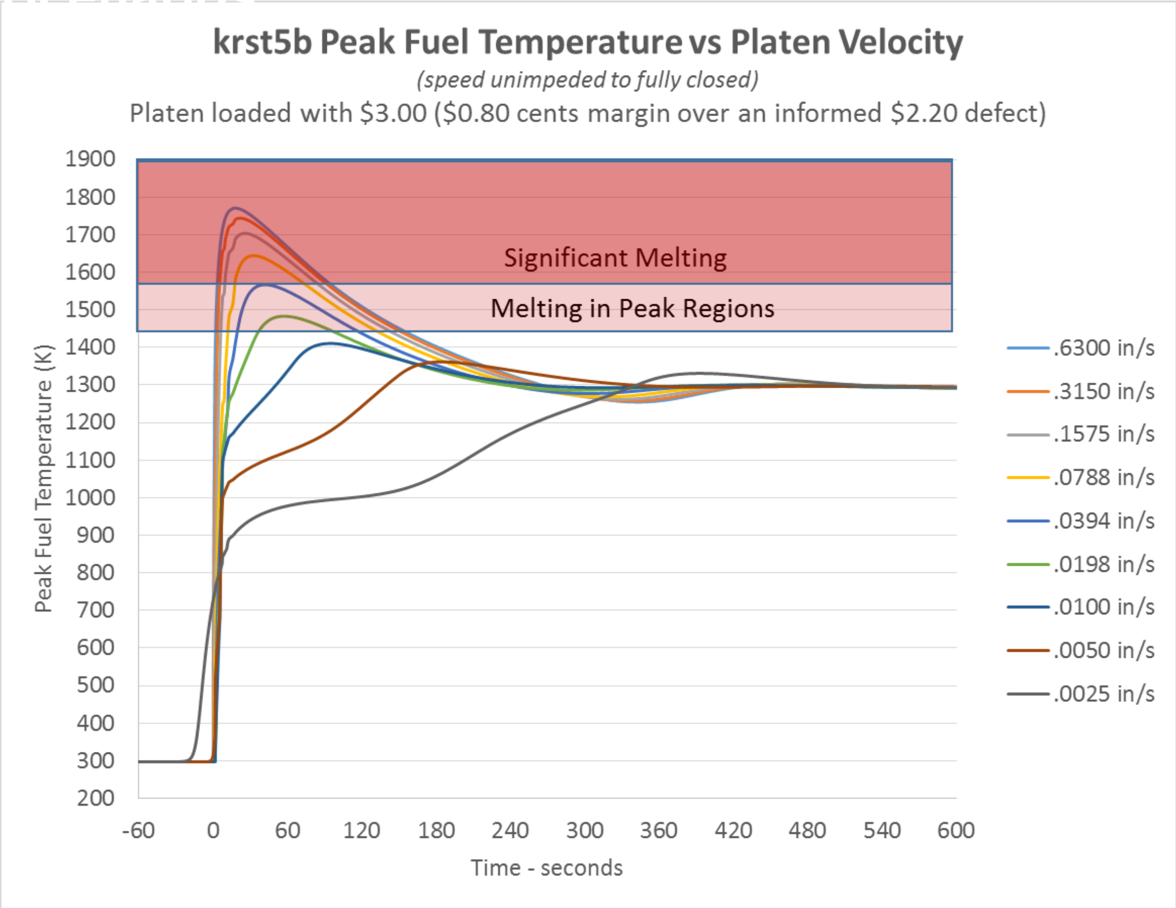

These calculations showed how fast the platen insertion rate would have to be to melt fuel.

There were 4 protections in place to ensure this scenario didn't happen.

1) KRUSTY would have to be loaded with more excess reactivity than planned (either by physical or computational error).
2) The speed limiting software on COMET would have to fail; it is programmed to limit speed as a function of closure gap.
3) The operator would need to mistakenly engage the joystick to continuously raise the platen against procedure.
4) The fail-safe scram system would fail to trip based on the excessively high power (neutron flux) caused by the transient.

Test Prep at the DAF

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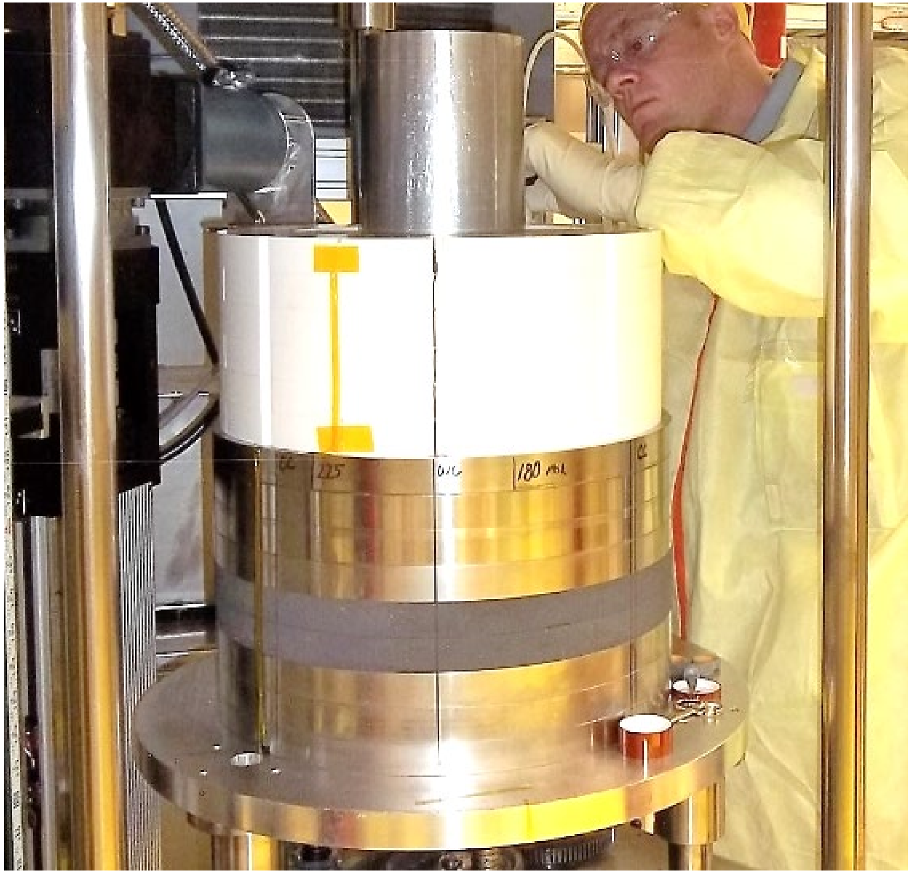

Component Zero-Power Crits

Rene Config #	BeO Height [inches]	B4C height (inches)	Shim Beo Height (inches)	Source Flag	Axref Flag	Fuel Flag (idaf)	Config Flag (idaf2)	Zcrit		Target at 295K (21.85C)	vlookup	Calc minus exper
0 ,	11.250 ,	0.000 ,	0.0 ,	1 ,	0 ,	3 ,	4 ,	0				
1 ,	11.250 ,	0.000 ,	0.0 ,	1 ,	0 ,	3 ,	4 ,	0	1	7.0	7.6	0.6
5 ,	11.375 ,	0.000 ,	0.0 ,	1 ,	0 ,	3 ,	4 ,	0	5	49.6	49.7	0.1
6 ,	11.250 ,	0.000 ,	0.0 ,	0 ,	0 ,	3 ,	4 ,	0	6	1.2	1.8	0.6
7 ,	11.375 ,	0.000 ,	0.0 ,	0 ,	0 ,	3 ,	4 ,	0	7	44.1	44.0	-0.1
8 ,	11.375 ,	0.000 ,	0.0 ,	3 ,	0 ,	3 ,	4 ,	0	8	46.4	47.3	0.9
10 ,	11.250 ,	0.000 ,	0.0 ,	4 ,	0 ,	3 ,	4 ,	0	10	3.0	3.1	0.0
13 ,	11.375 ,	0.000 ,	0.0 ,	4 ,	0 ,	3 ,	4 ,	0	13	47.3	45.6	-1.7
14 ,	11.375 ,	0.000 ,	0.0 ,	4 ,	2 ,	3 ,	4 ,	0	14	5.6	5.9	0.2
15 ,	11.375 ,	0.000 ,	0.0 ,	4 ,	1 ,	3 ,	4 ,	0	15	31.8	31.8	0.0
17 ,	11.500 ,	0.000 ,	0.0 ,	4 ,	3 ,	3 ,	4 ,	0	17	27.1	26.6	-0.5
18 ,	11.375 ,	0.000 ,	0.0 ,	2 ,	0 ,	3 ,	4 ,	0	18	46.8	45.3	-1.5
19 ,	11.250 ,	0.000 ,	0.0 ,	2 ,	0 ,	3 ,	4 ,	0	19	3.9	1.9	-2.0
20 ,	11.375 ,	0.125 ,	0.0 ,	2 ,	0 ,	3 ,	4 ,	0	20	15.9	15.1	-0.8
21 ,	11.500 ,	0.250 ,	0.0 ,	2 ,	0 ,	3 ,	4 ,	0	21	44.1	42.1	-2.1
25 ,	11.500 ,	0.625 ,	0.0 ,	2 ,	0 ,	3 ,	4 ,	0	25	11.5	9.7	-1.8
26 ,	11.625 ,	0.625 ,	0.0 ,	2 ,	0 ,	3 ,	4 ,	0	26	53.0	51.0	-2.0
29 ,	11.250 ,	0.000 ,	-0.99 ,	2 ,	0 ,	3 ,	4 ,	0	29	16.9	14.1	-2.8
30 ,	10.375 ,	0.000 ,	2.0 ,	2 ,	0 ,	3 ,	4 ,	0	30	45.5	42.8	-2.7
33 ,	10.625 ,	1.000 ,	2.0 ,	2 ,	0 ,	3 ,	4 ,	0	33	41.1	44.0	2.9
34 ,	10.625 ,	1.125 ,	2.0 ,	2 ,	0 ,	3 ,	4 ,	0	34	30.7	33.5	2.8
35 ,	10.750 ,	2.000 ,	2.0 ,	2 ,	0 ,	3 ,	4 ,	0	35	2.9	2.4	-0.5
36 ,	10.875 ,	2.000 ,	2.0 ,	2 ,	0 ,	3 ,	4 ,	0	36	55.7	56.3	0.5
39 ,	10.875 ,	2.500 ,	2.0 ,	2 ,	0 ,	3 ,	4 ,	0	39	0.0	0.1	0.1
40 ,	11.000 ,	2.500 ,	2.0 ,	2 ,	0 ,	3 ,	4 ,	0	40	52.6	52.6	0.0
41 ,	11.125 ,	3.000 ,	2.0 ,	2 ,	0 ,	3 ,	4 ,	0	41	43.6	44.4	0.9
42 ,	11.375 ,	4.000 ,	2.0 ,	2 ,	0 ,	3 ,	4 ,	0	42	11.3	13.8	2.5
43 ,	10.875 ,	0.000 ,	2.0 ,	2 ,	0 ,	3 ,	1 ,	0	43	55.7	58.2	2.5

Over 70 total critical configurations measured.

MCNP and ENDF7 cross sections matches results very well.

Component criticals did not include heat pipes, clamps, vacuum vessel and insulation – to get better “purer” nuclear data for benchmarking.

Measurements of BeO radial reflector worth were used to verify how much BeO should be loaded for final test (we needed ~$1.65 of excess reactivity to reach 800 C.

KRUSTY Assembly Zero Power Crits

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Rene Config #		BeO Height [inches]		B4C height (inches)		Shim Beo Height (inches)		Source Flag		Axref Flag		Fuel Flag (idaf)		Config Flag (idaf2)		Zcrit		Target at 295K (21.85C)	vlookup	Calc minus exper
44	,	10.750	,	0.000	,	2.0	,	2	,	0	,	3	,	1	,	0	44	7.7	11.6	3.9
45	,	10.875	,	0.125	,	2.0	,	2	,	0	,	3	,	1	,	0	45	27.3	31.4	4.1
47	,	10.875	,	0.375	,	2.0	,	2	,	0	,	3	,	1	,	0	47	3.4	8.1	4.7
48	,	11.000	,	0.375	,	2.0	,	2	,	0	,	3	,	1	,	0	48	50.3	54.1	3.8
53	,	11.000	,	1.000	,	2.0	,	2	,	0	,	3	,	1	,	0	53	5.1	8.8	3.7
54	,	11.125	,	1.000	,	2.0	,	2	,	0	,	3	,	1	,	0	54	51.4	54.6	3.2
59	,	11.125	,	1.625	,	2.0	,	2	,	0	,	3	,	1	,	0	59	0.9	3.4	2.5
60	,	11.250	,	1.625	,	2.0	,	2	,	0	,	3	,	1	,	0	60	46.9	48.2	1.4
63	,	11.250	,	2.000	,	2.0	,	2	,	0	,	3	,	1	,	0	63	11.4	13.5	2.1
64	,	11.375	,	2.000	,	2.0	,	2	,	0	,	3	,	1	,	0	64	56.4	57.6	1.2
68	,	11.375	,	2.500	,	2.0	,	2	,	0	,	3	,	1	,	0	68	2.3	6.2	3.8
69	,	11.500	,	2.500	,	2.0	,	2	,	0	,	3	,	1	,	0	69	46.2	49.5	3.3
72	,	11.500	,	2.875	,	2.0	,	2	,	0	,	3	,	1	,	0	72	4.1	7.1	3.0
73	,	11.625	,	2.875	,	2.0	,	2	,	0	,	3	,	1	,	0	73	46.5	48.7	2.1
74	,	11.625	,	3.250	,	2.0	,	2	,	0	,	3	,	1	,	0	74	0.6	4.4	3.8
75	,	11.750	,	3.250	,	2.0	,	2	,	0	,	3	,	1	,	0	75	40.0	43.7	3.7
76	,	11.750	,	3.500	,	2.0	,	2	,	0	,	3	,	1	,	0	76	6.5	12.5	6.0
77	,	11.125	,	0.000	,	1.0	,	2	,	0	,	3	,	1	,	0	77	41.2	43.0	1.8
78	,	11.125	,	0.125	,	1.0	,	2	,	0	,	3	,	1	,	0	78	13.5	15.9	2.4
79	,	11.250	,	0.125	,	1.0	,	2	,	0	,	3	,	1	,	0	79	55.0	56.3	1.3
80	,	11.250	,	0.500	,	1.0	,	2	,	0	,	3	,	1	,	0	80	22.0	23.5	1.5
81	,	11.375	,	0.500	,	1.0	,	2	,	0	,	3	,	1	,	0	81	62.5	63.8	1.3
82	,	11.375	,	1.000	,	1.0	,	2	,	0	,	3	,	1	,	0	82	26.7	27.9	1.2
83	,	11.500	,	1.000	,	1.0	,	2	,	0	,	3	,	1	,	0	83	66.2	66.2	0.0
84	,	11.500	,	1.500	,	1.0	,	2	,	0	,	3	,	1	,	0	84	27.6	26.6	-1.0
85	,	11.625	,	1.500	,	1.0	,	2	,	0	,	3	,	1	,	0	85	65.5	63.5	-2.0
86	,	11.625	,	2.000	,	1.0	,	2	,	0	,	3	,	1	,	0	86	20.7	18.5	-2.2
87	,	11.750	,	2.000	,	1.0	,	2	,	0	,	3	,	1	,	0	87	56.1	53.2	-2.9
88	,	11.750	,	2.500	,	1.0	,	2	,	0	,	3	,	1	,	0	88	3.1	1.3	-1.7
90	,	11.625	,	0.000	,	1.0	,	2	,	0	,	3	,	1	,	0.665	90	14.9	14.0	-1.0
91	,	11.625	,	0.000	,	1.0	,	2	,	0	,	3	,	1	,	0.618	91	29.8	28.6	-1.2

B4C rod measurements were made to benchmark flight control rod – plus poison was needed to allow additional BeO loading (without exceeding 80 cents of excess).

B4C Central Rod Worth

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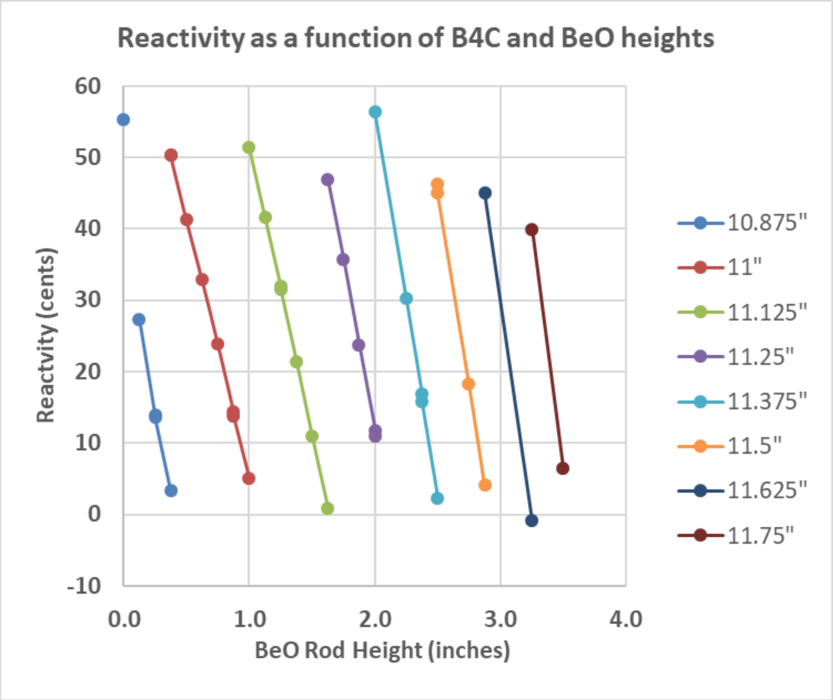

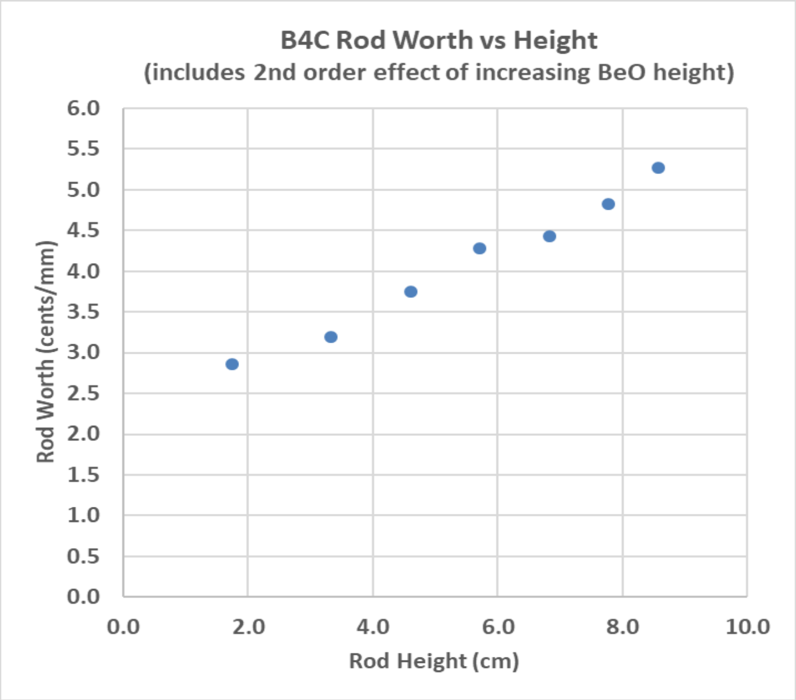

The reactivity worth of the B4C rod matched MCNP predictions extremely well, these measurement are very important since the flight system will move this rod to change reactivity instead of move the reflector.

The great thing about these kind of compact-fast reactors is that they behave as point-kinetic reactors (i.e. the mean free path of the neutron is relatively large (>3cm) as compared to the core dimensions; therefore the reactor behavior will be the same whether reactivity is added by withdrawing the rod vs raising the reflector (except for minor differences in power peaking).

KRUSTY 15 cent free run – first nuclear power!

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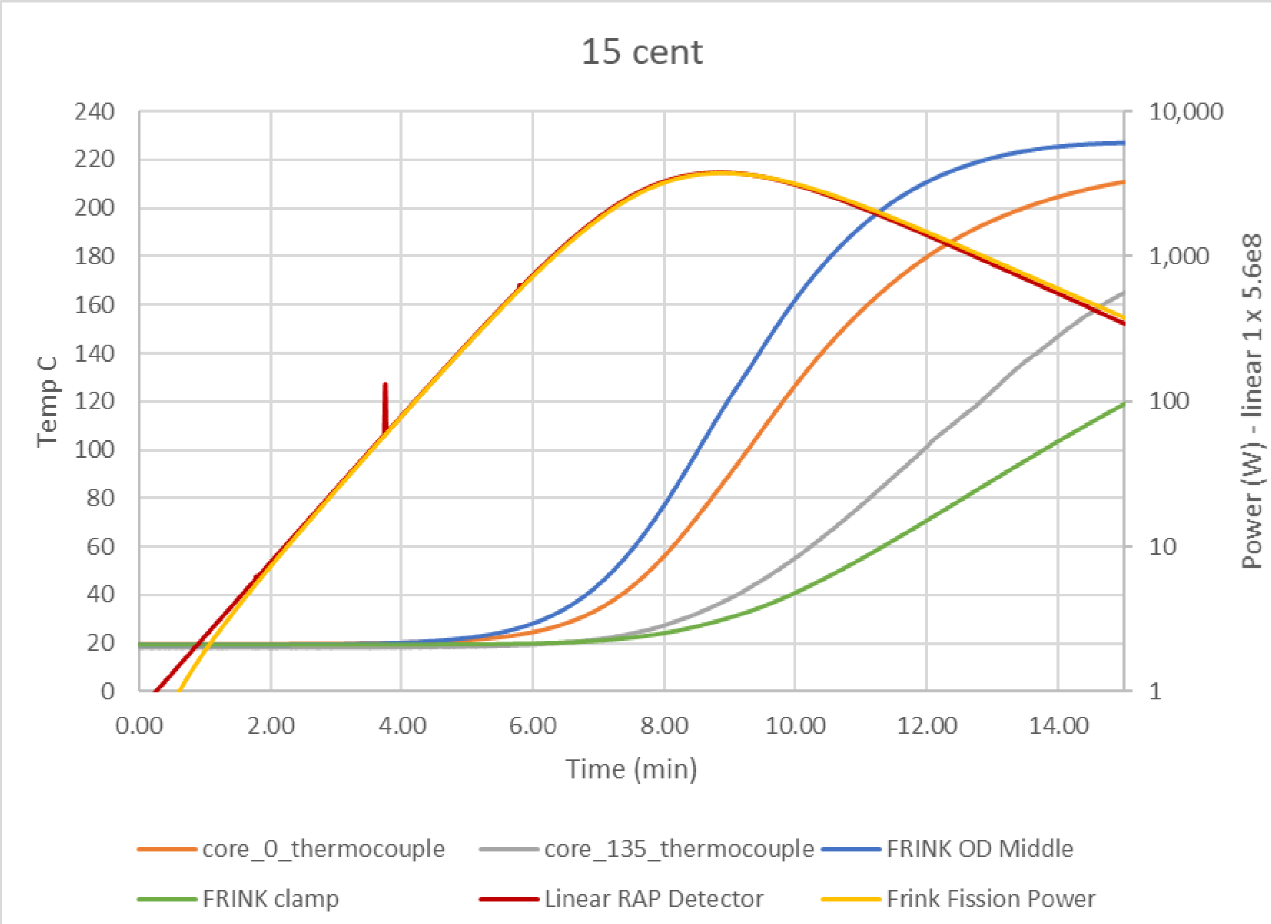

Some TCs had better thermal bonding than others, and only one TC was well bonded (the orange line), which reached ~220 C. As the subsequent tests went to higher temperatures, the thermal-bonding got much better; which is to be expected, since the TCs are spring-loaded against the fuel (not physically attached). It was decided not to weld or braze the TCs directly to the fuel to avoid potential fuel damage, but unfortunately this caused significant lag in most of the core temperature TCs.

KRUSTY Core and Reflector

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Note the thermocouple wires in middle photo, under the core clamping rings, and the TC placed in the BeO reflector on right photo.

KRUSTY 15 cent free run

KRUSTY

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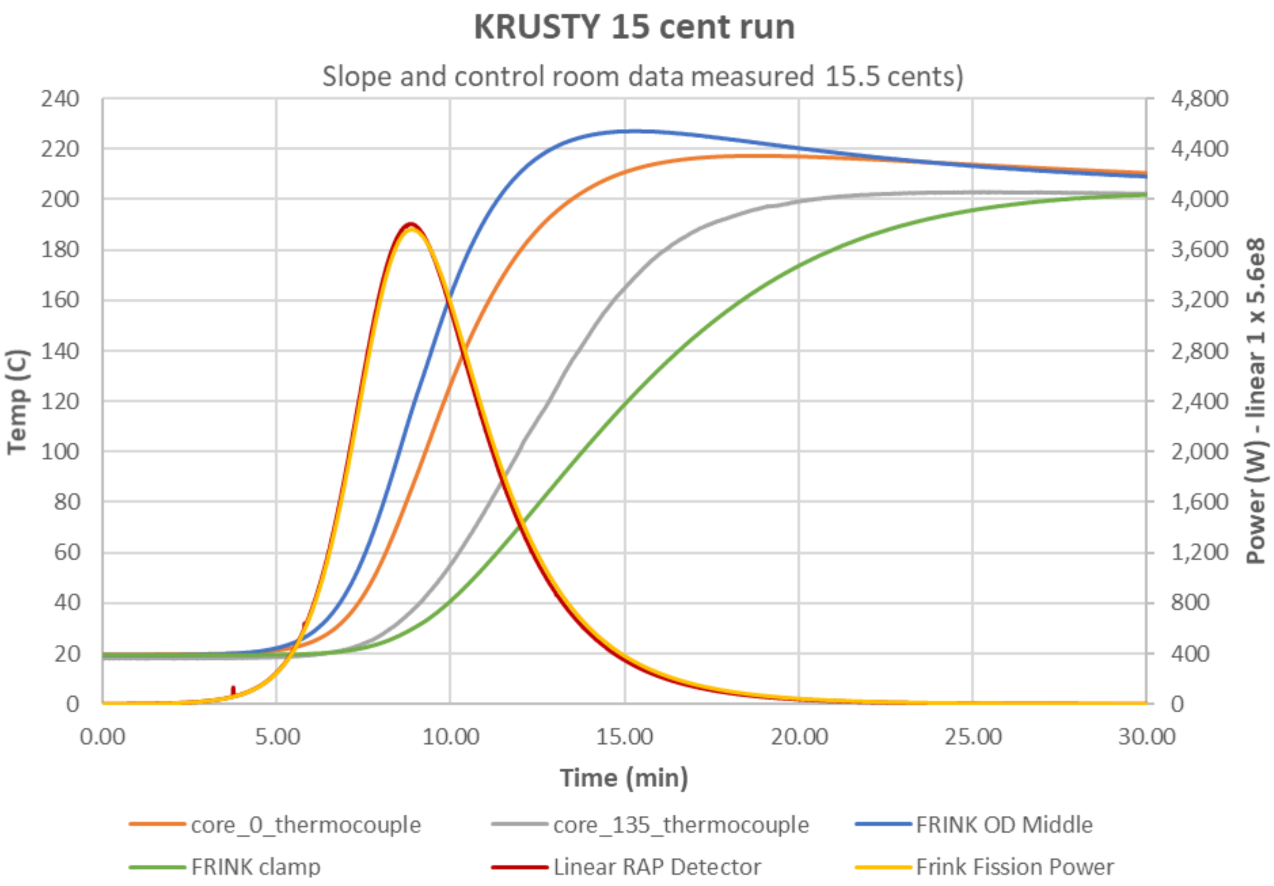

15 cent free run was the first fission-powered test, great for benchmarking because it is the only test where total reactivity insertion is well defined, thus the simplest test to calibrate fission power with room neutron count (Amps from the He-3 detector) – based on temperature rise and the thermal inertia.

Summary of KRUSTY RTCs

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Each of the RTCs is in polynomial form via a curve fit, which are used in FRINK, except for radial mli, for which a constant value was used based on the defect.

Component	Temp	Defect	Integral RTC at Operating Temp	Instantaneous RTC at Op. Temp
	(K)	(cents)	(cents/K)	(cents/K)
Fuel	1075	-134.6	-0.1727	-0.2042
Axial Reflector	415	0.3	0.0024	0.0026
Heat Pipes	1050	-3.3	-0.0044	-0.0042
Brackets	1045	-2.3	-0.0031	-0.0026
Multi-Foil Insul.	805	-0.7	-0.0014	-0.0014
Vacuum Vessel	375	3.3	0.0422	0.0431
Radial Reflector	310	0.0	0.0019	0.0007
Platen Shielding	309	0.3	0.0239	0.0239
Radial Shielding	295.2	0	-0.0663	-0.0663

Fuel expansion feedback dominates reactor transient behavior

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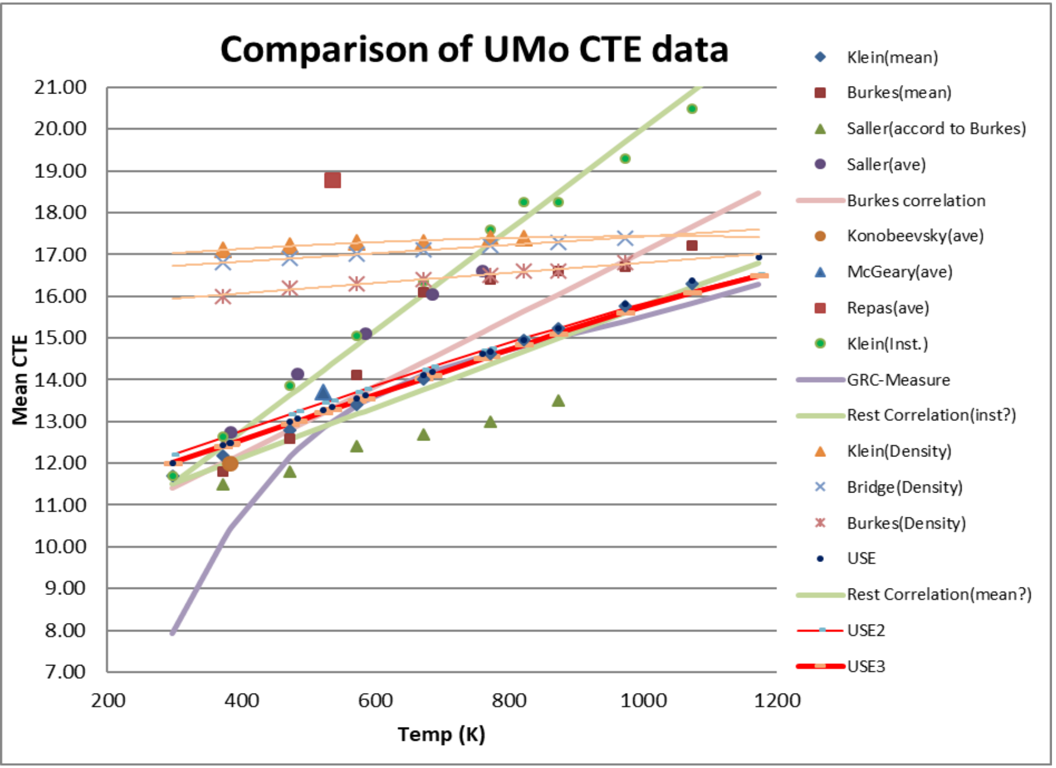
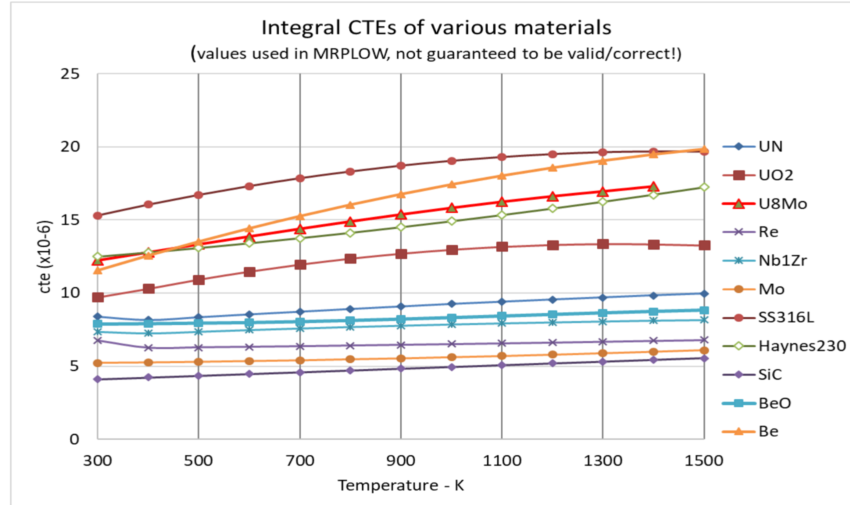
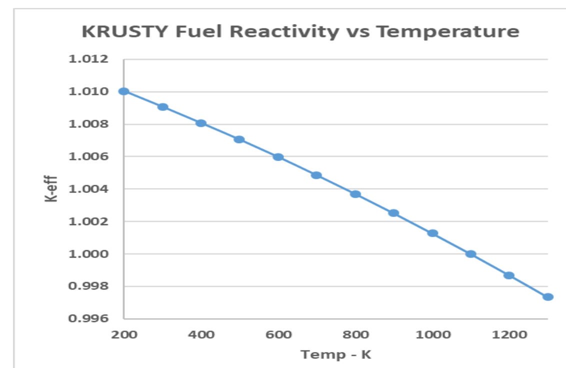




UMo cte is well matched with steel and nickel alloys.

Lots of confusing data concerning UMo cte. The key was creating our own data with actual fuel samples from Y-12 (which had its own issues at low temps) – we went with red line, which matched performance very well.



KRUSTY 15 cent free run – longer term

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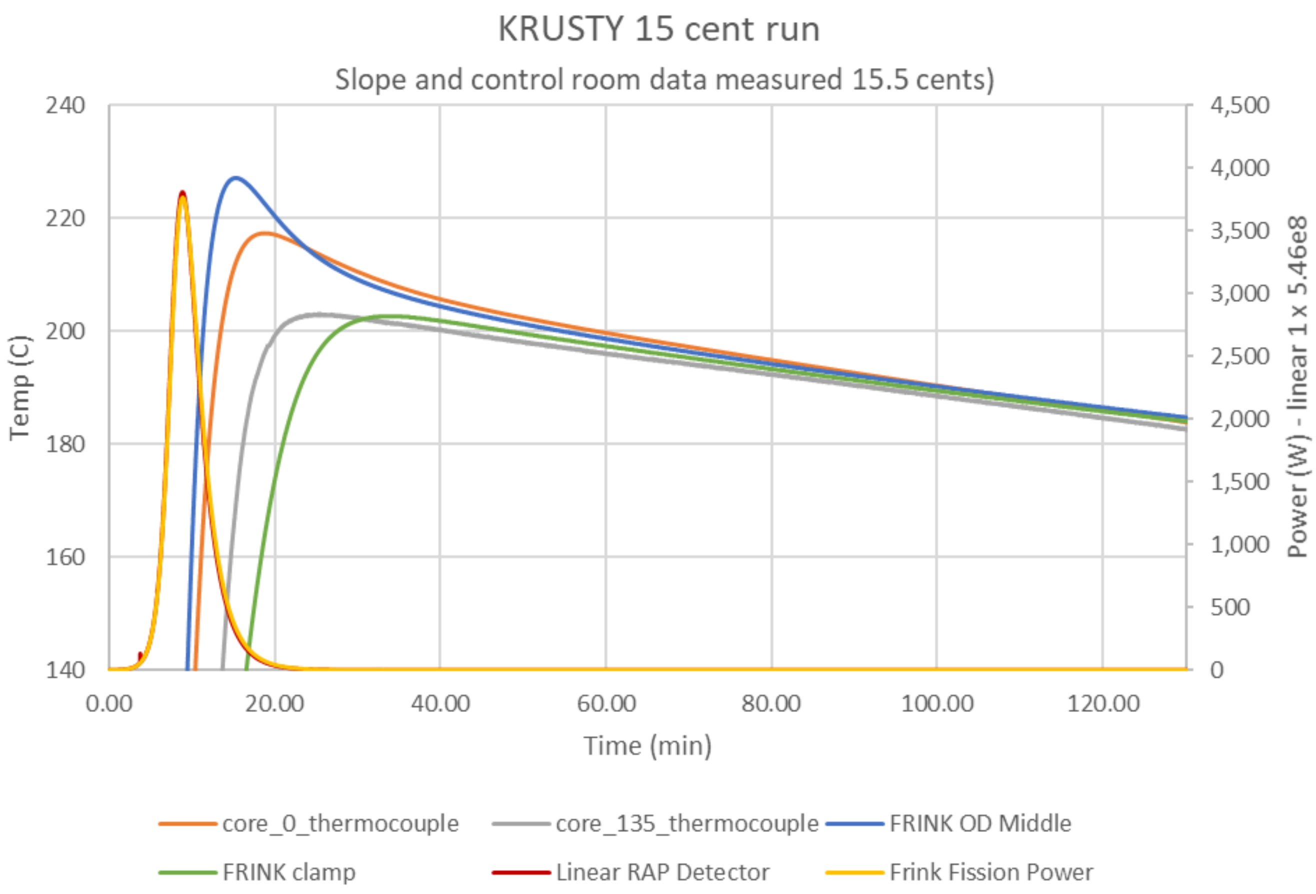
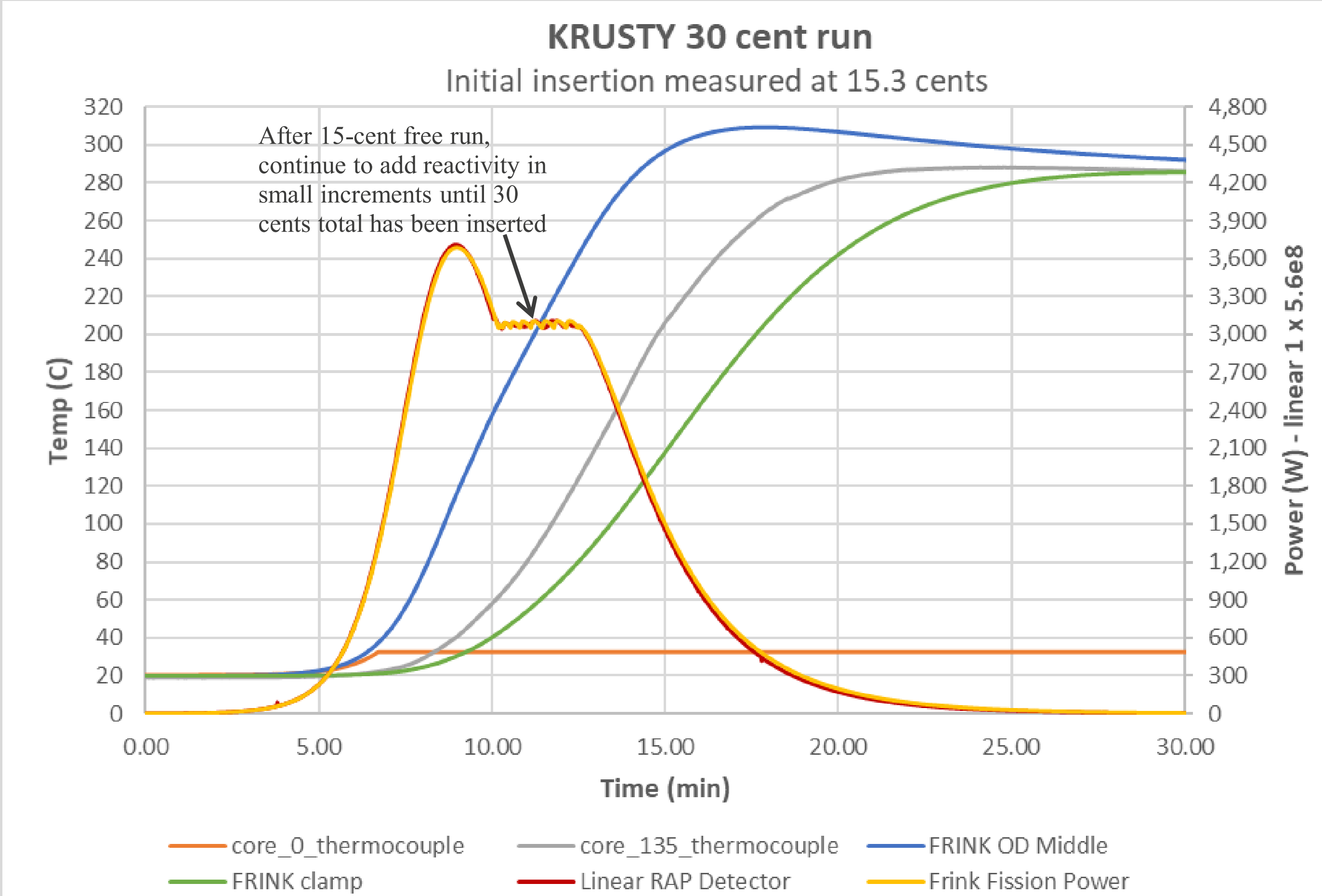


The slow drop in temperature provides data to determine thermal losses (based on thermal inertia). The 30 and 60 cent runs inferred the power losses and subsequently higher temperatures. Important, because heat transfer through 10+ layers of mli is impossible to accurately predict, but can be benchmarked with several datapoints (mostly to determine the ratio of conduction to radiation).

KRUSTY 30 cent run



All nuclear tests started with 15-cent free run, the additional reactivity was inserted to raise temperature – the reactivity was inserted at a rate to keep the power level at ~3 kWth.

Unfortunately, the only “well-bonded” TC died at about the 7-min mark (the orange line), but we were very fortunate to have it for at least the 15 cent run. It was the only TC lost during the nuclear testing, while several were lost during the electrical test. In the end we had 9 “good” TCs our of 18 installed (i.e. good, but not well bonded at low temp).

KRUSTY 60 cent run

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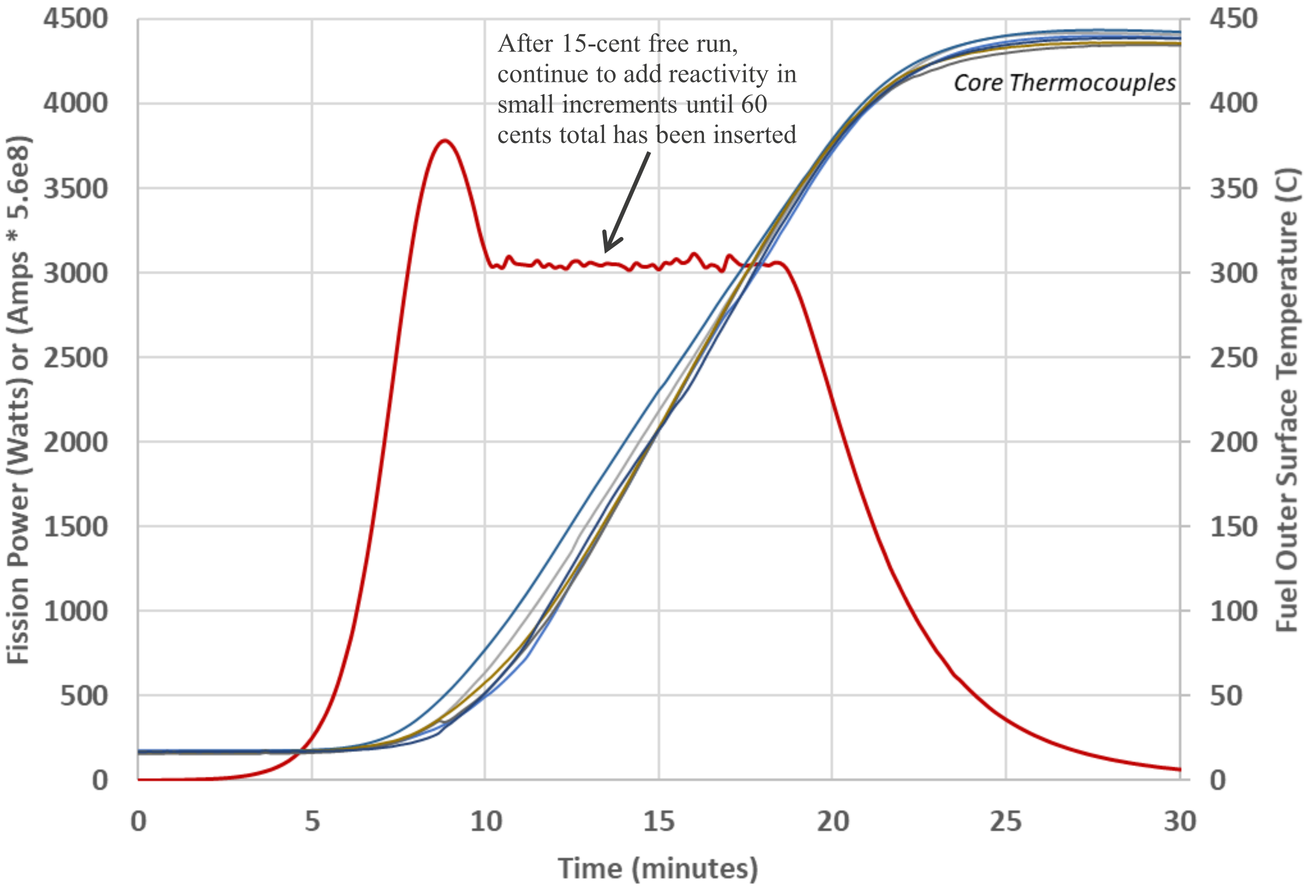
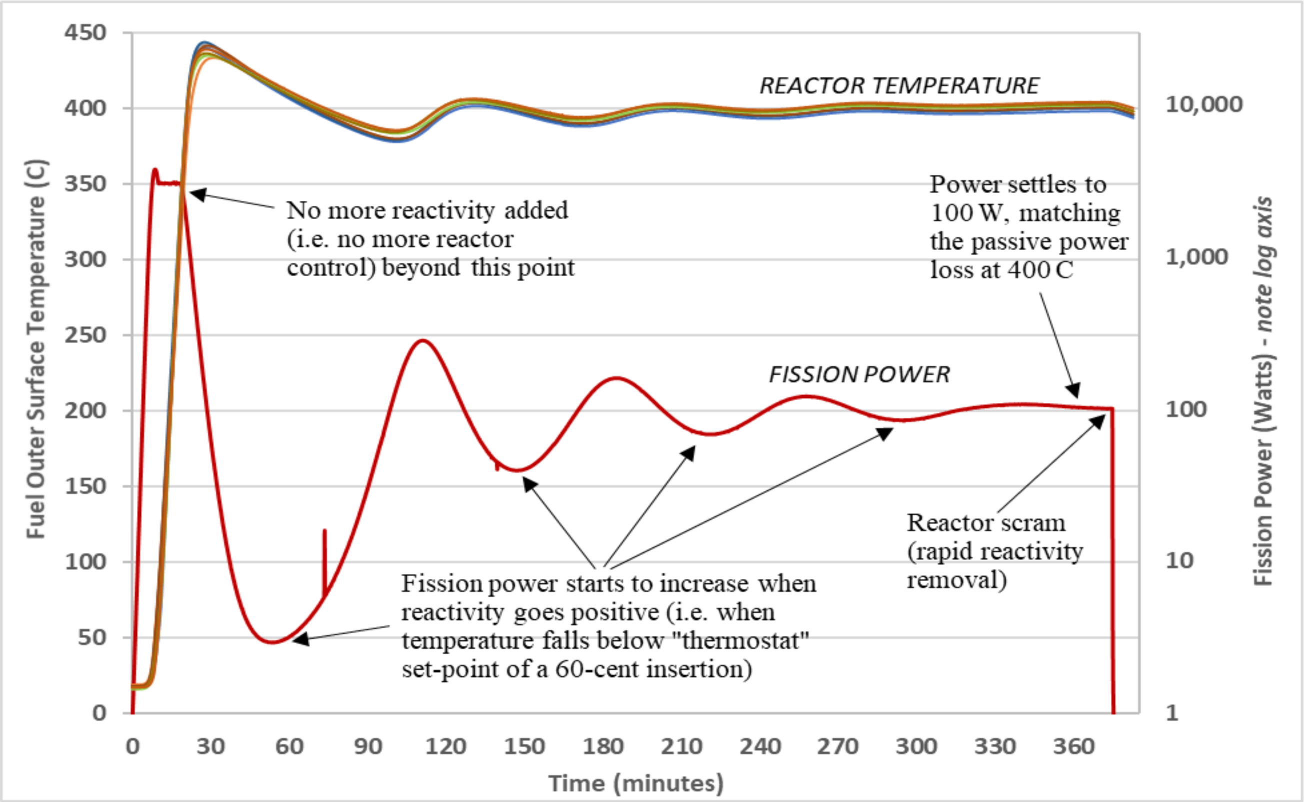


The 60 cent run was the go no-go point of the KRUSTY campaign. KRUSTY was a new reactor type, and only the design team had the capability to perform transient analyses. The regulator (DOE) agreed to a safety basis that relied our ability to predict how the system would perform; i.e. we claimed how simple and predictable reactor performance would be, and they said put your money where your mouth is. We had to predict peak core temperature +/- 10%. The pretest peak temperature prediction was 447 C, actual was 446 C.(well within 10%, even in C, although to add margin McClure had negotiated in K!

KRUSTY 60 cent run

The 60-cent critical proved the simple, stable, passive behavior of the KRUSTY reactor.

In the case below, the reactivity "thermostat" was set so the fuel wants to maintain a temperature of 400 C.

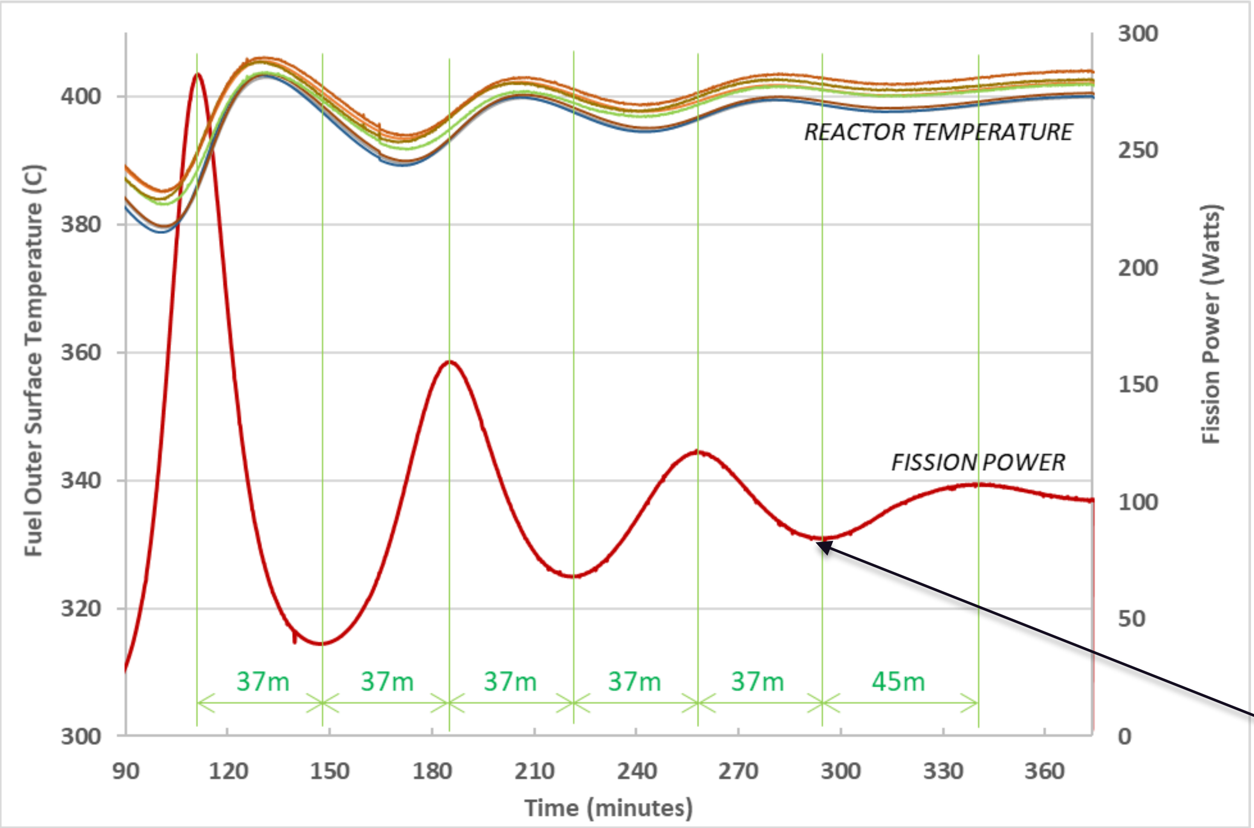


The period of oscillation is rather long in this example (75 minutes) because the passive power draw is very low (only 100 Watts) – just as lower gravity would make a pendulum take longer to swing back and forth.

The 15-cent run would have had a period of several hours, while the full system test had a period of ~15 minutes at ~3 kWt. The period is mostly a factor of power and thermal inertia. A higher feedback coefficient will actually lengthen period a bit, with smaller temperature amplitude.

KRUSTY 60 cent run...
A loud failure produces subtle result

KRUSTY
Fission Power to Enable Space Exploration



Extremely loud grinding noise heard (over hot microphone) at 296 minutes. Noise lasted for about 30 seconds as the turbo pump failed.

Pressure increased from 1e-4 to 1e-2 Torr (roughing pumps could hold it there, at least at this relatively cold Rx temperature)

It actually produced an interesting result, as the decrease in vacuum cooled the fuel a bit a slowed the temperature rise of the next oscillation.

Turbopump failure, vacuum reduced

KRUSTY Power Conversion

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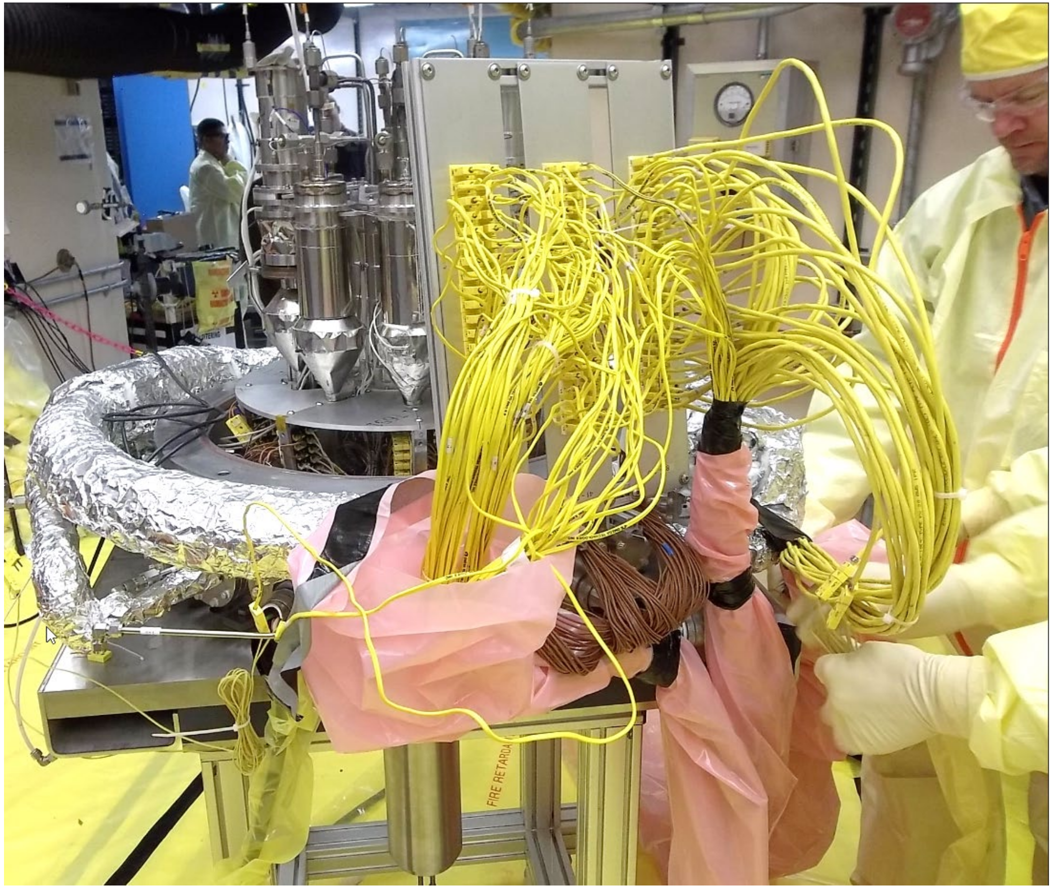

KRUSTY Calculated Axial Power Peaking for Full-Power Testing

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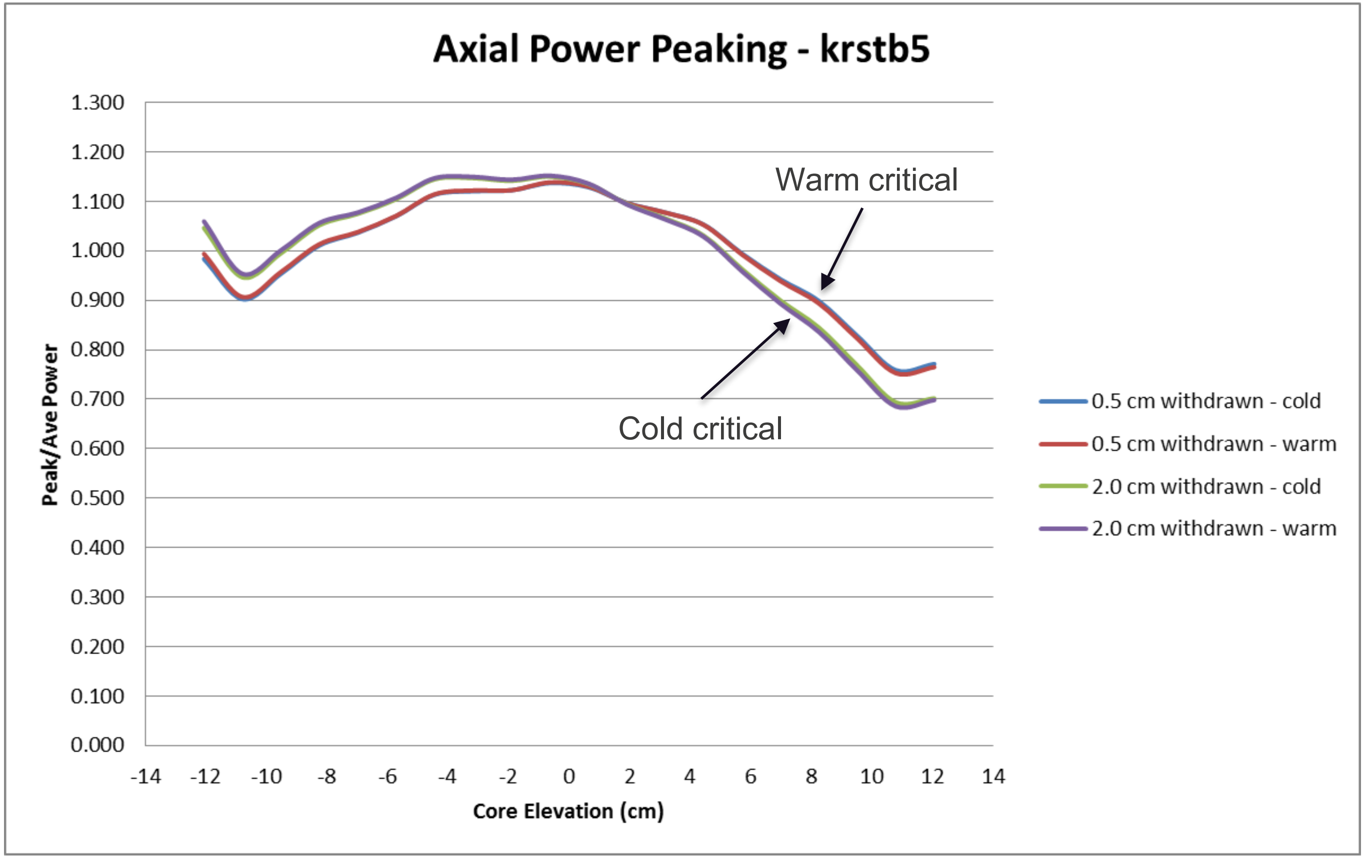
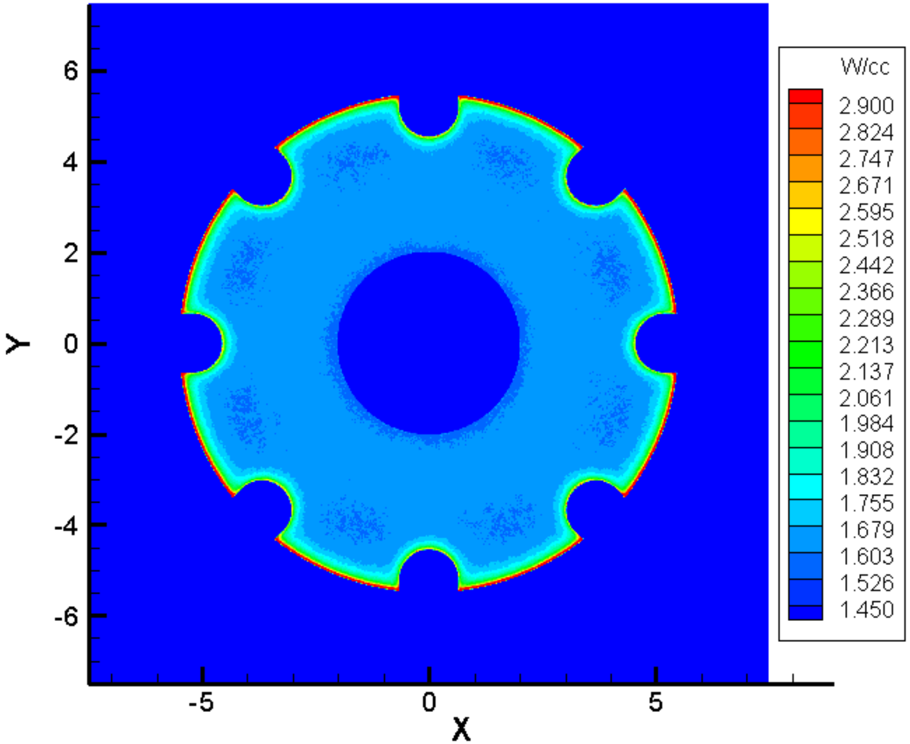
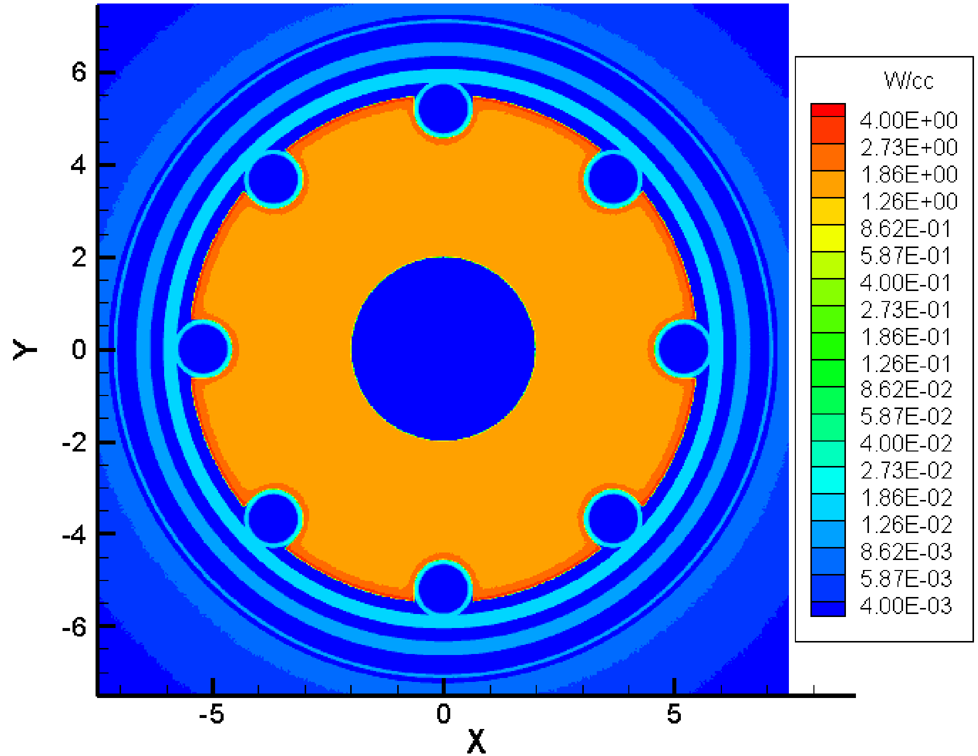


This level of axial peaking is small compared to most reactors, despite the fact that we have an extremely large L/D.

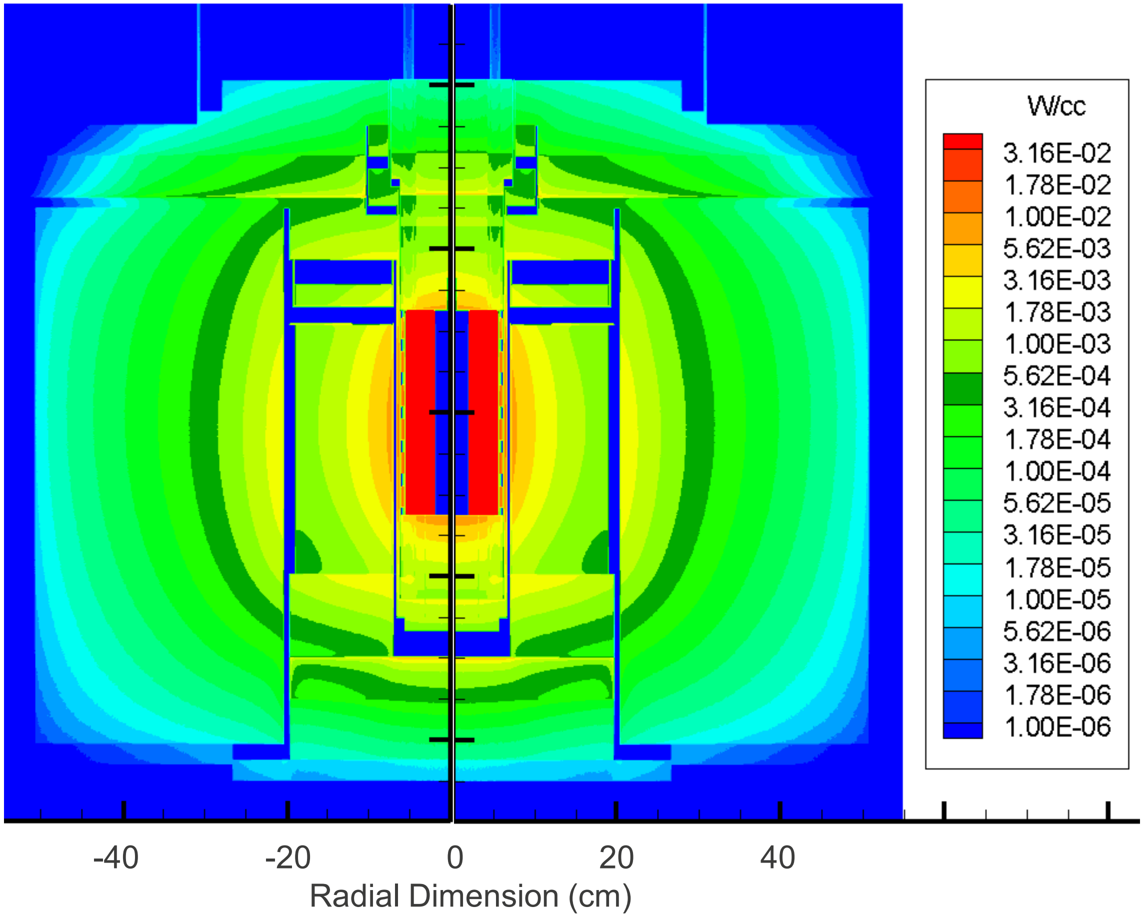
The effect of the core clamps is distinguishable – 5 relative peaks occur at the location between the clamps. However, the “peaks” are ~1% of power, so the net impact is minor.

KRUSTY Calculated Radial Core Power Deposition





Radial power is pretty flat, and slightly tilted outward. This outer peaking layer is so thin that localized heat-up is not a significant issue, plus the outer layer radiates to the clamps and insulation.



Power deposition in the shield means it is "doing its job", reducing energy deposition (Rads) outside of the system.

The system model deposits power into each component to calculate temperatures and thermal balance.

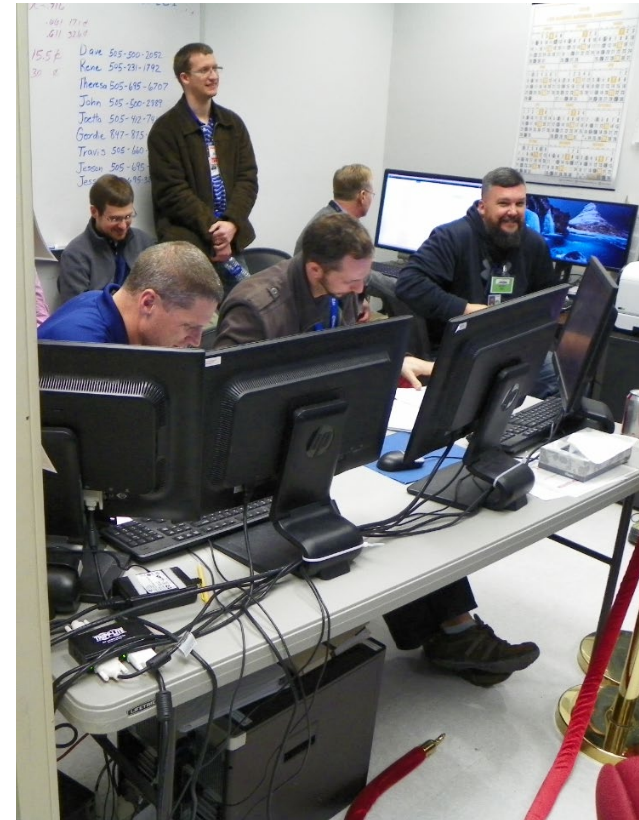
Component (not all listed)	Watts (3kW)
heat pipes	1.79
fuel	2816.15
clamps	3.20
multifoil	0.74
radial vessel	3.57
radref sleeve	0.90
radref	47.81
radial shield	86.33
upper axref	1.81
lower axref	2.98
upper external B4C shield	7.39
lower B4C shield	4.32

NCERC Control Room at DAF in Nevada

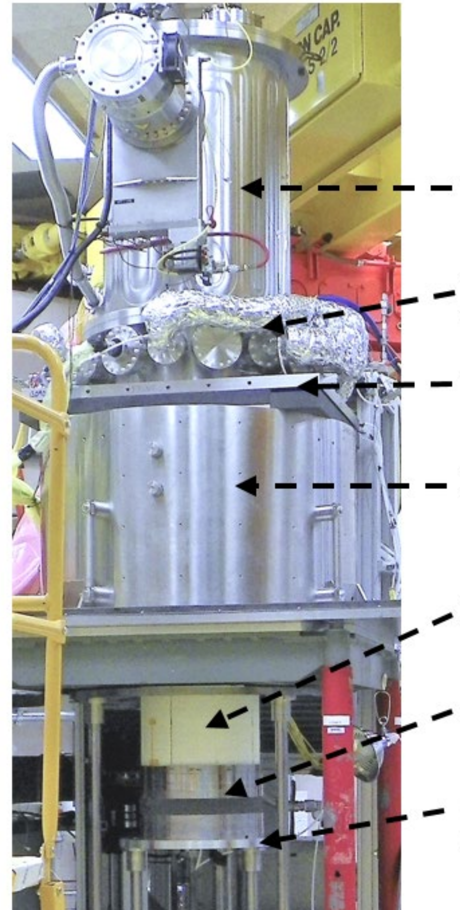
Front Panels COMET / Rear Panels KRUSTY

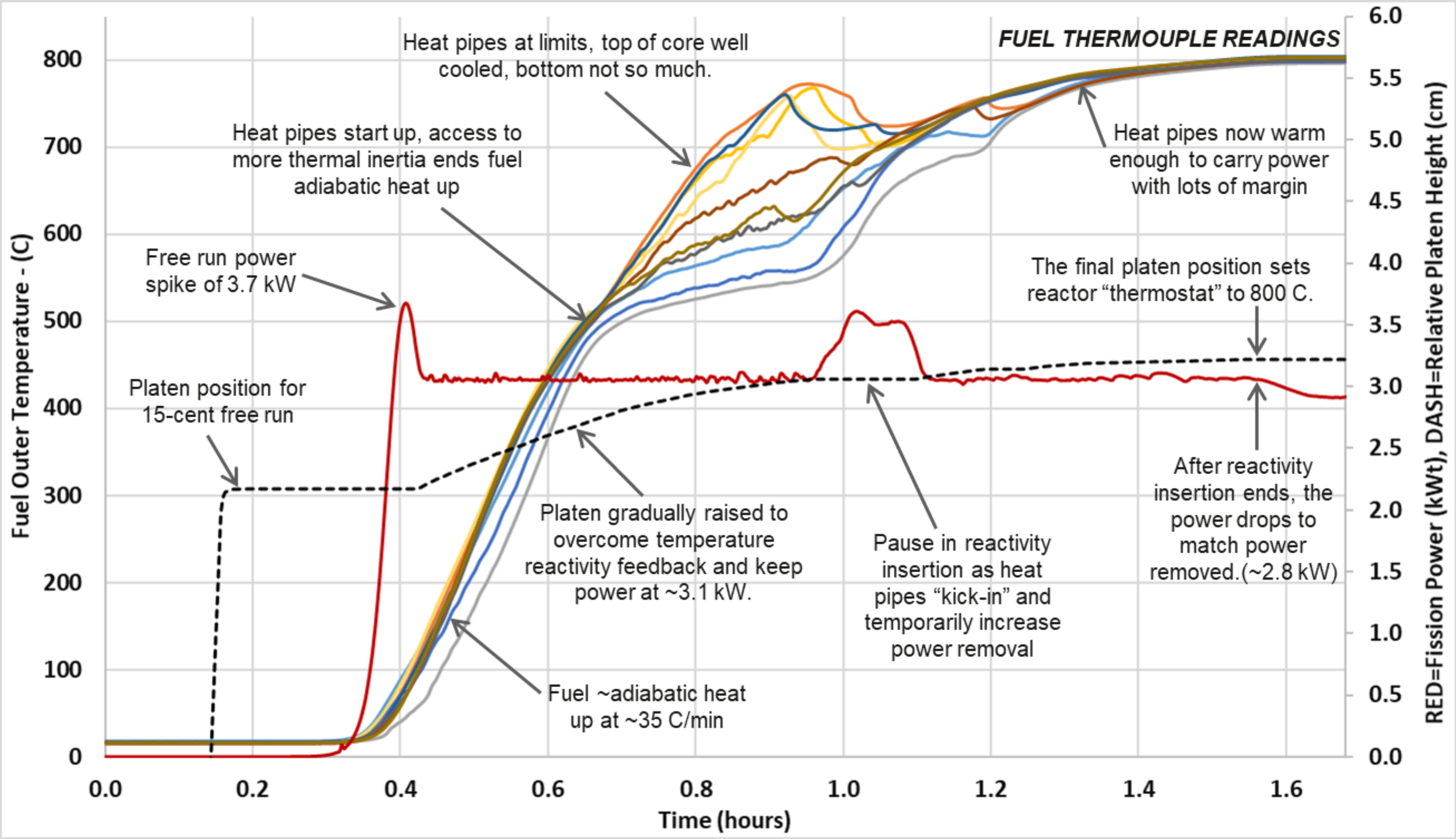
KRUSTY

Fission Power to Enable Space Exploration



KRUSTY Final Configuration




FUEL THERMOUPLE READINGS
Heat pipes at limits, top of core well cooled, bottom not so much.
Heat pipes start up, access to more thermal inertia ends fuel adiabatic heat up
Free run power spike of 3.7 kW
Platen position for 15-cent free run
Heat pipes now warm enough to carry power with lots of margin
The final platen position sets reactor “thermostat” to 800 C.
Platen gradually raised to overcome temperature reactivity feedback and keep power at ~3.1 kW.
Pause in reactivity insertion as heat pipes “kick-in” and temporarily increase power removal
After reactivity insertion ends, the power drops to match power removed.(~2.8 kW)
Fuel ~adiabatic heat up at ~35 C/min
Fuel Outer Temperature - (C)
0
100
200
300
400
500
600
700
800
RED=Fission Power (kWt), DASH=Relative Platen Height (cm)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Time (hours)

KRUSTY Heat Pipes

KRUSTY
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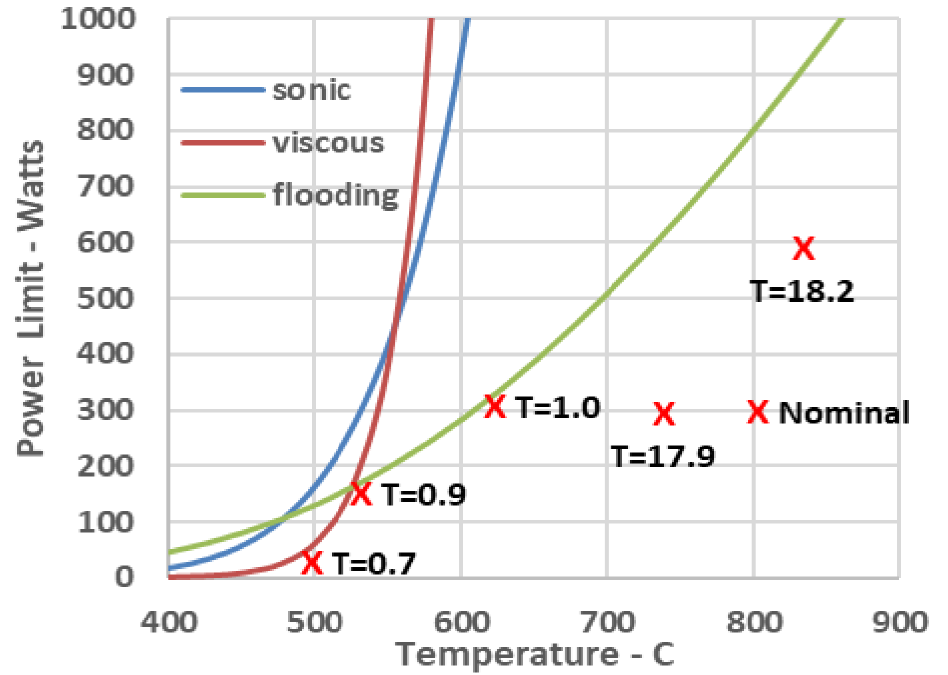
- **Wall material: Haynes-230**
- **Wick material: Nickel (pool/evaporator region only)**
- **Working fluid: Sodium**



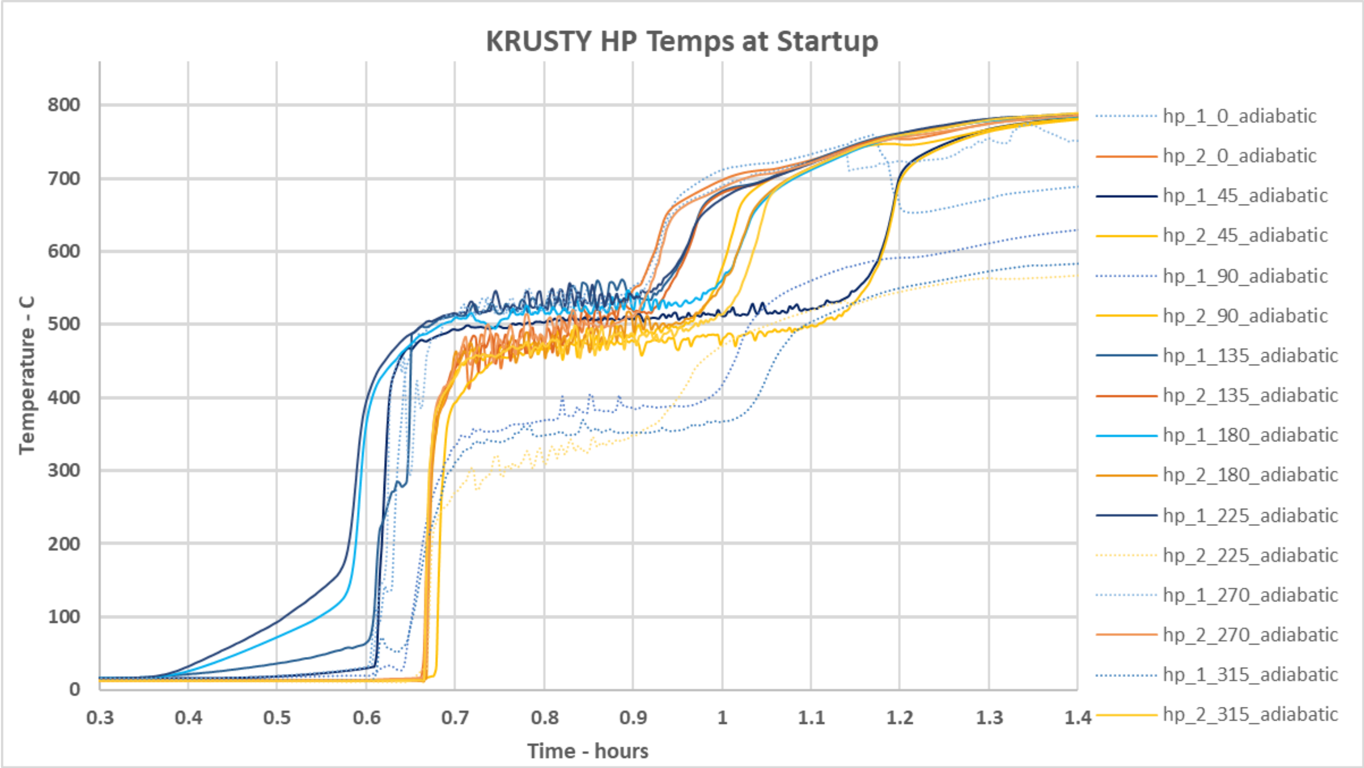
X marks KRUSTY heat pipe conditions at the denoted time

The heat pipes operate with thermosiphon action outside of the core, which resulted with a flooding limit that dictated power throughput at temperatures over 800 K.

Overall, the KRUSTY heat pipes performed beautifully when power demand was within limits, and very squirrelly (as expected) when operating at thermal limits.

Once adequately warmed-up, the heat pipes behaved effectively as an infinite conductor – which greatly simplifies system dynamic response on control.

Heat pipe temperature startup data



The blue thermocouples show when the thaw front reached just outside the core (in 2 cases conduction was enough to start the warm-up), the yellow thermocouples are ~50 cm further up the heat pipe, and the Na thaw front reaches there a ~4 minutes later. The dotted TC curves did not appear to be reading correctly. The squiggles at ~500 C again show where the heat pipes were struggling against their limits

Several components cause reactivity feedback, but fuel dominates. Graphs shown are calculations

KRUSTY

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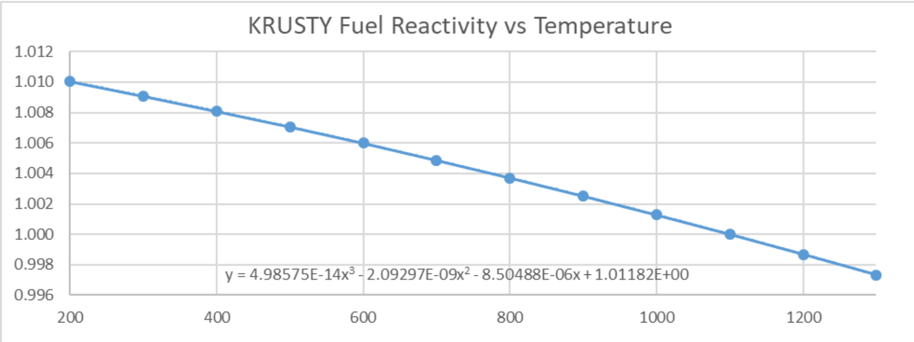

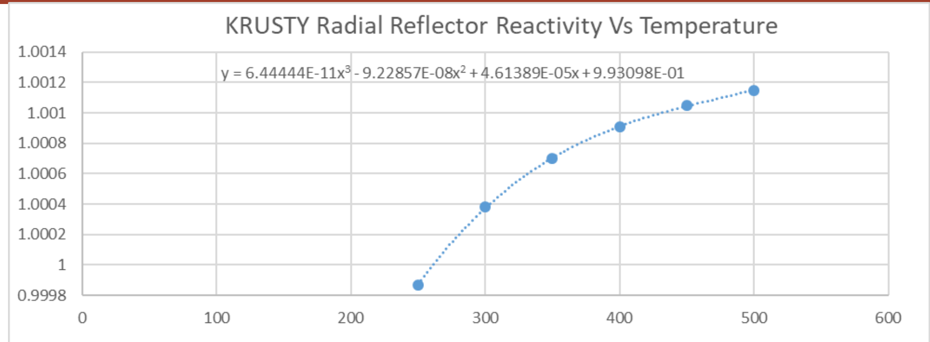

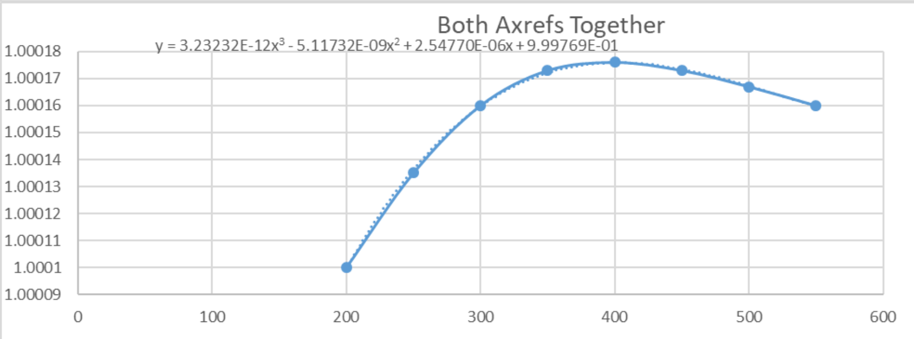

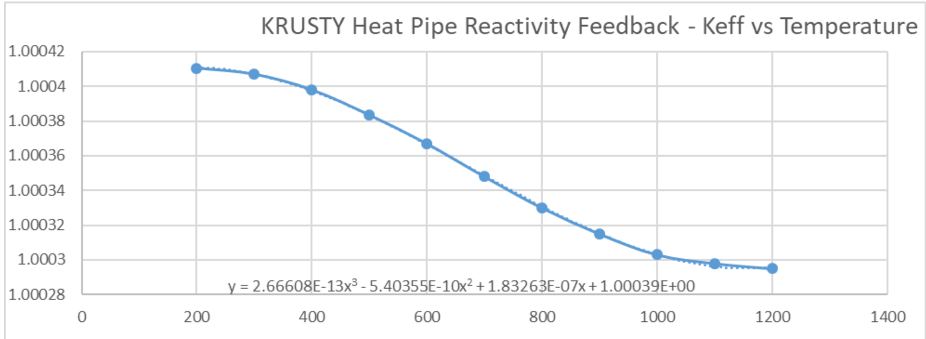

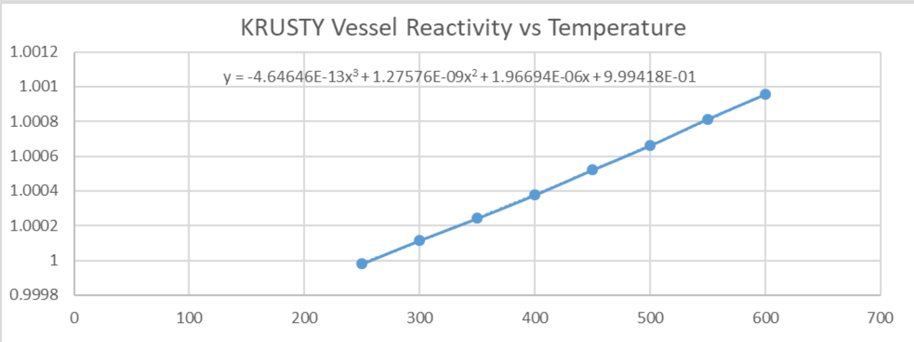

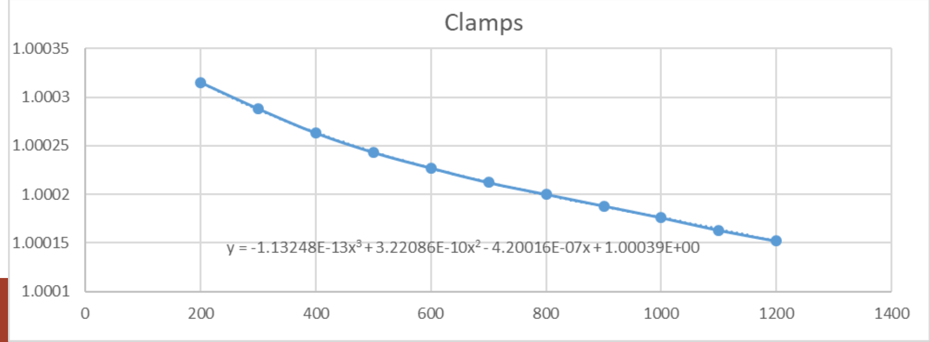

Approach to steady-state data

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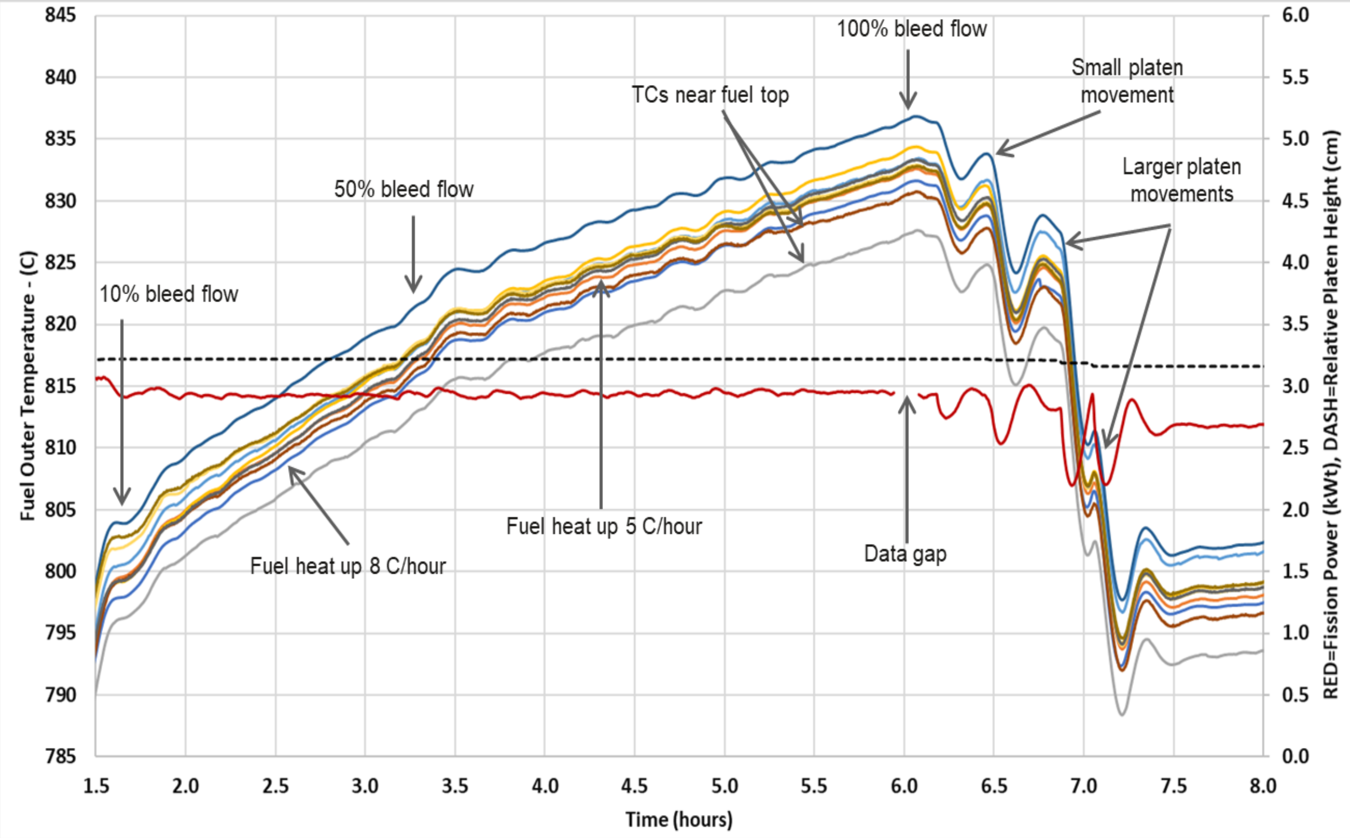

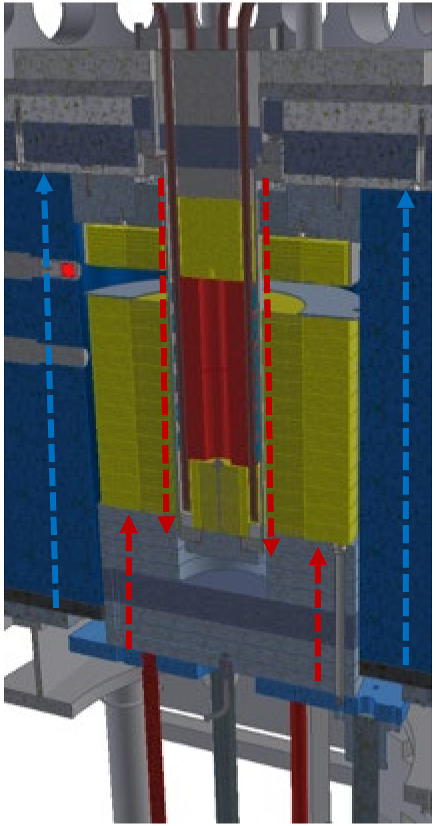

A lot going on here. Described in Nuclear Technology "Results of the KRUSTY Nuclear System Test"

KRUSTY Load Following Transient Data

(first operational data from new reactor concept in US in >40 years!)

KRUSTY

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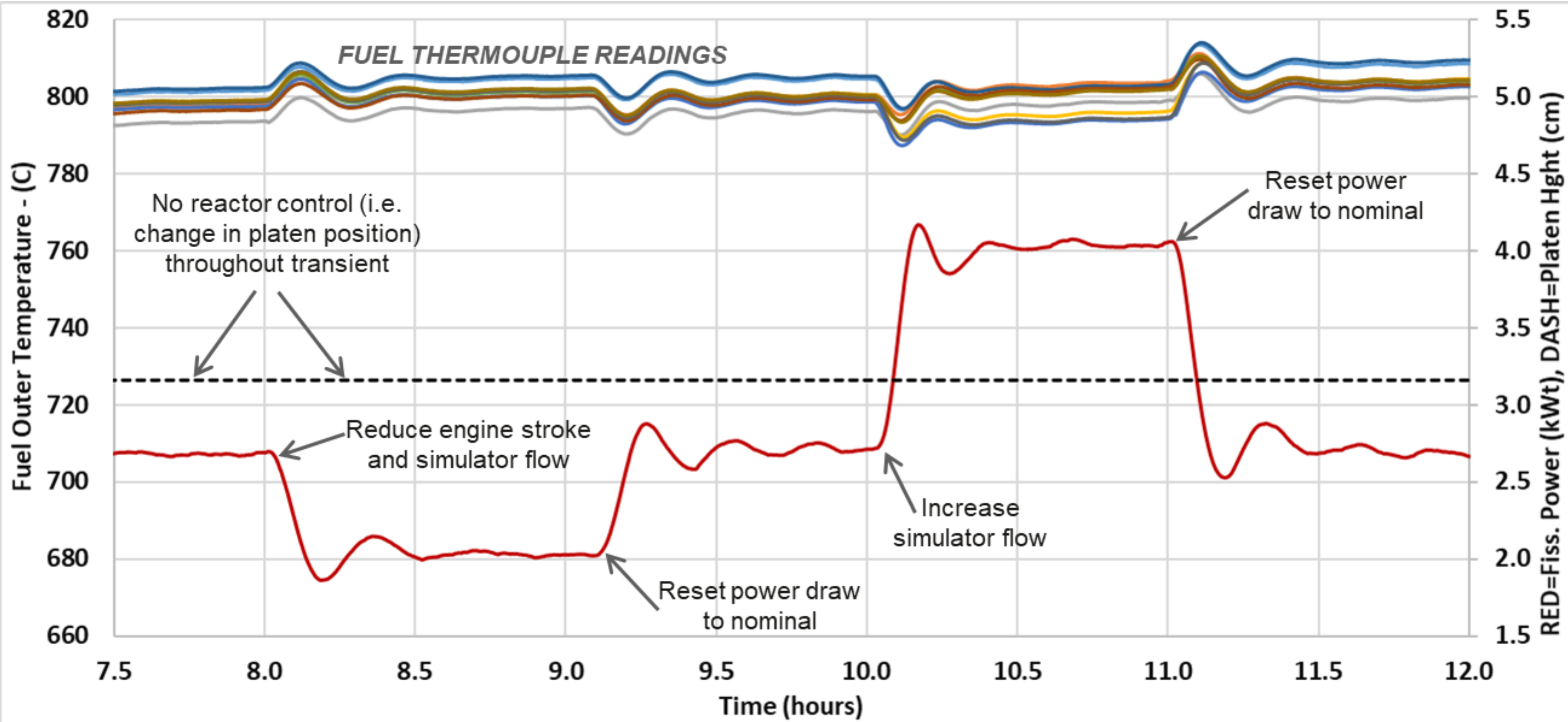
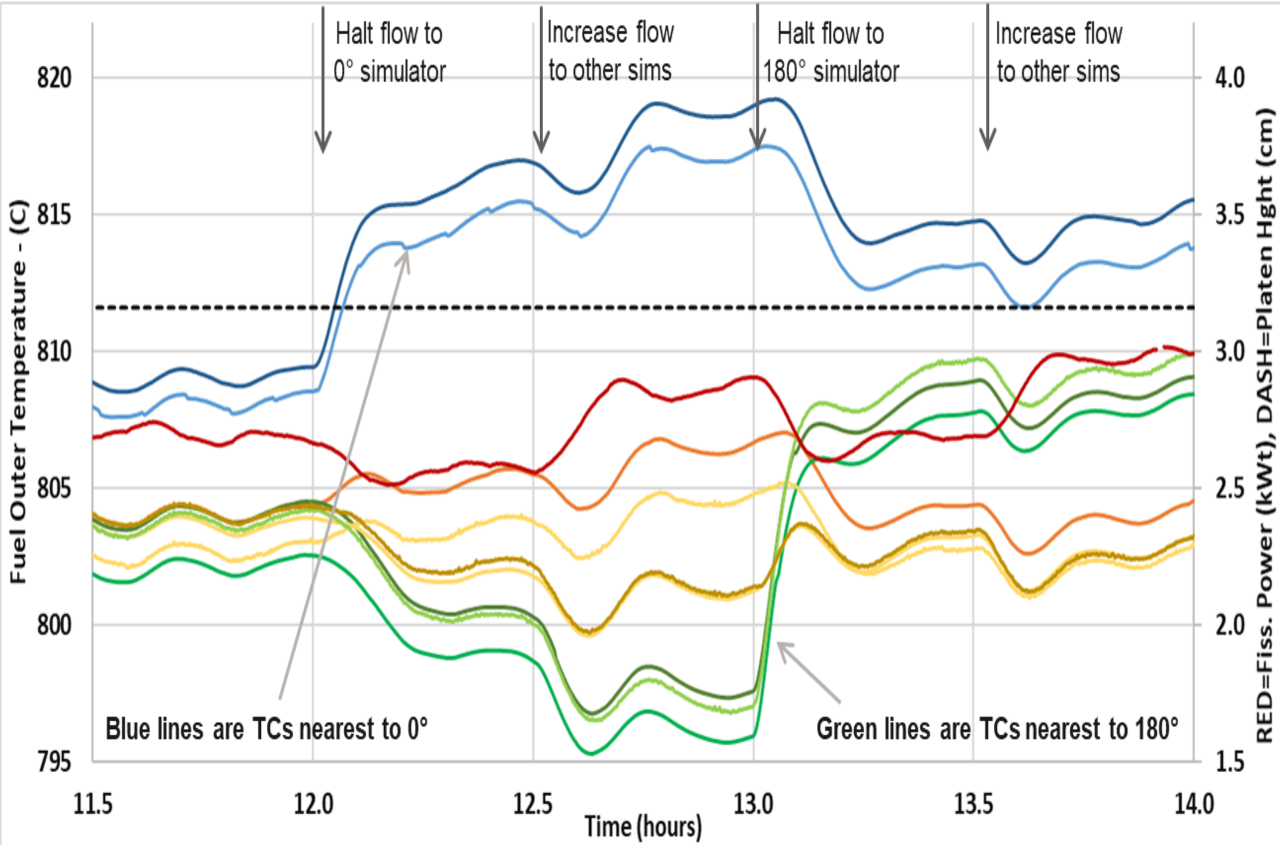
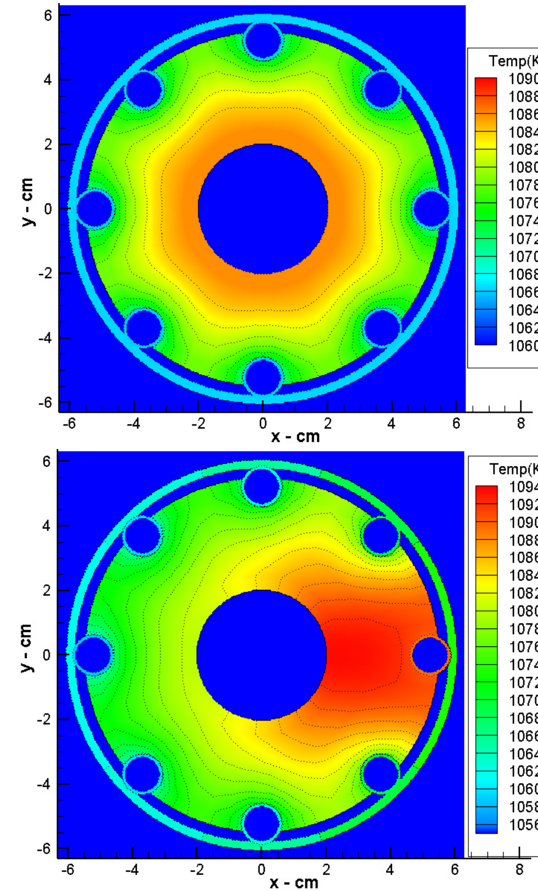


The coup de gras – the reactor thermal power matches the power draw, in order to main the reactivity thermostat set-point (reactivity is zero, k-eff=1 at 800 C, except for minor 2nd order effects).

KRUSTY Fault Tolerance Transient Data





Fault tolerance is proven as expected. A failure in a Stirling “string” (convertor or heat pipe) can easily be tolerated in the core

Above plots are from model

KRUSTY Reactivity Adjustment Transient Data

KRUSTY

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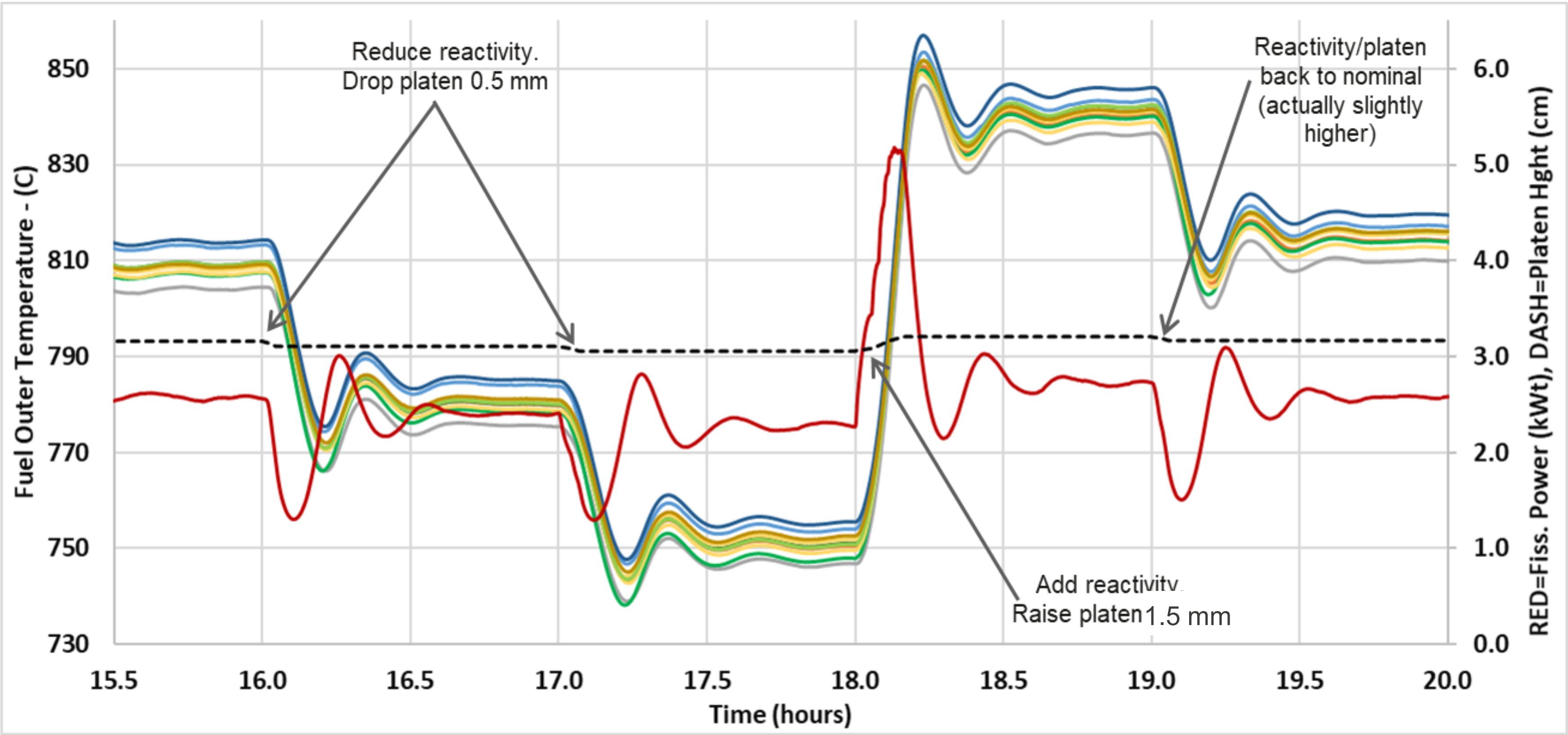

KRUSTY Nuclear System Test Overview

KRUSTY

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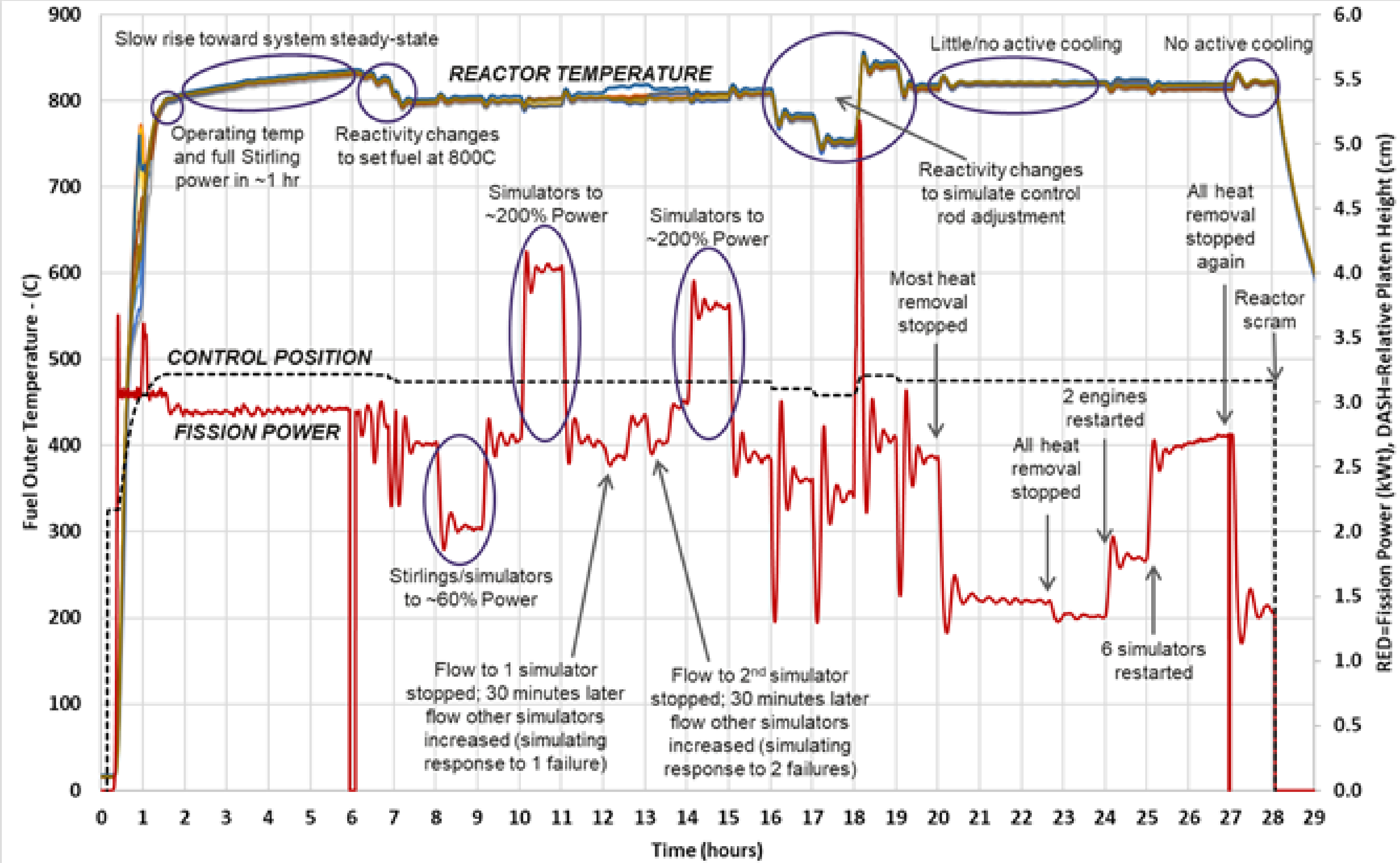

Our goal was to get as many transients done as we could within our agreed to 28 hours limit of powered operation (to limit activation of the room for future experiments).

Flexibility in the test plan was important, because of things learned in the previous weeks in prior tests, particularly the transient “settling” time.

The final test plan was emailed out a few hours before testing began.

Electrical Output – from 80 W-rated engines

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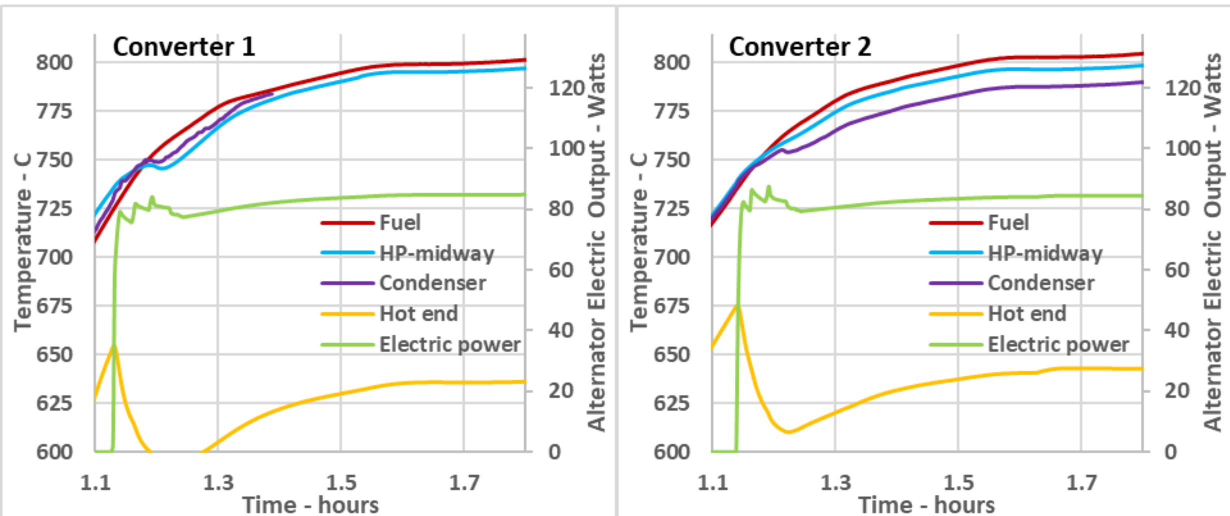
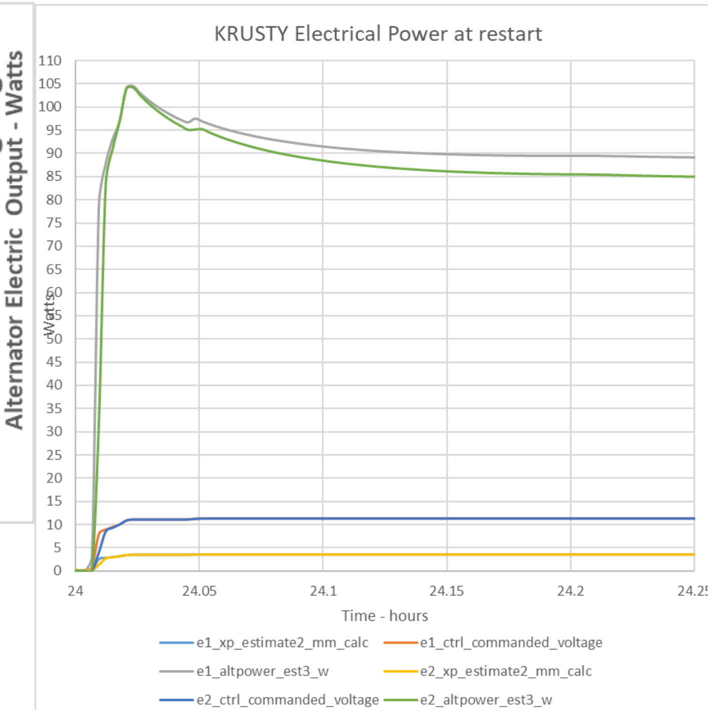
Startup



Restart



The Stirling convertors performed without a glitch during both electrical and nuclear system testing; including a restart where the hot-end was soaked to >800 C (way above spec); which not only successfully restarted, but provided over 100 We for a few minutes due to the high Carnot efficiency.

Flight vs. KRUSTY?

Nearly identical reactor performance

KRUSTY

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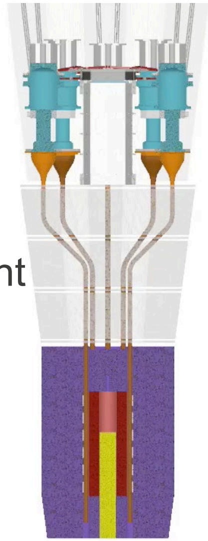
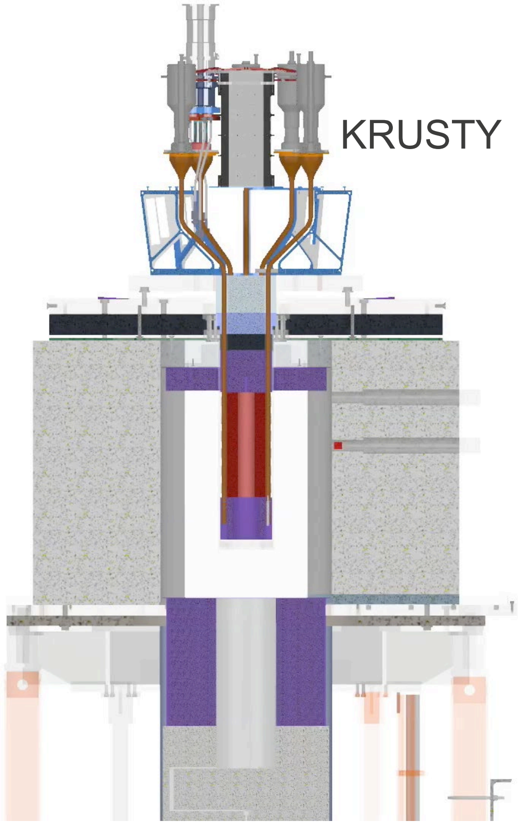




- The raising of the BeO reflector (KRUSTY) increases reactivity by decreasing neutron leakage, while withdrawing the B4C rod (Flight) increases reactivity by decreasing neutron absorption.
- This difference will cause minor effects on power distribution and feedback, but as far as the neutron population (i.e. power) is concerned, there is very little difference between the two reactivity mechanisms.
- This is because KRUSTY is a very good example of a point-kinetic reactor, which occurs when the neutron mean-free-path is a significant fraction of the core geometry. In such a system, all regions of the reactor communicate very well with each other.
- Thus, a 15-cent insertion, or any transient caused by moving the reflector will look almost identical to the same transient caused by moving the B4C rod.
- Also, the coupled thermal-nuclear behavior is nearly identical for a 1 kWe or 10 kWe reactor, or an HEU or LEU reactor, and equally as predictable as KRUSTY.
- **No nuclear-powered testing needed for Kilopower flight unit.**
- **True whether 1 kWe-HEU system or 25 kWe-LEU system.**

KRUSTY design "influences"

KRUSTY

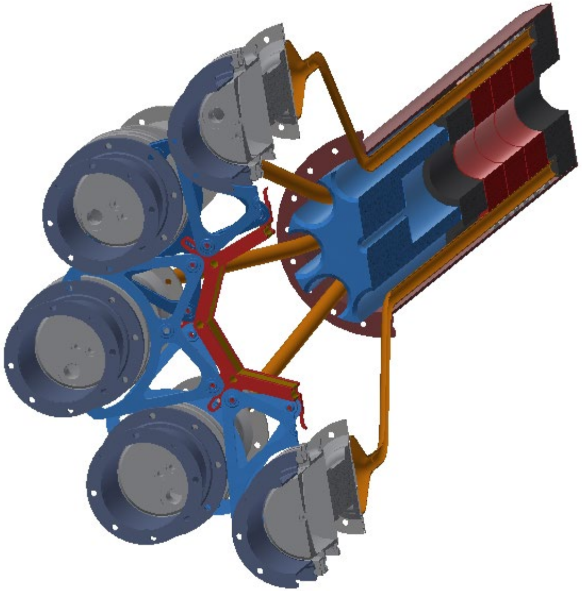
Fission Power to Enable Space Exploration

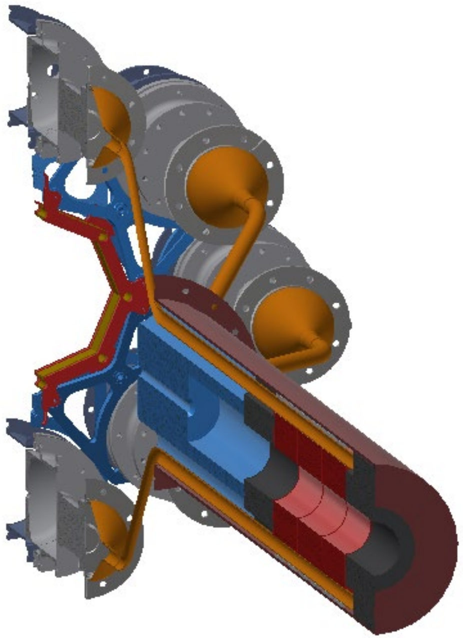
- **Dozens of significant factors (hundreds of daily minor factors) influence and constrain the design process.**
  - Try at all times to meet the "goals" of the experiment, and maximize value.
  - Ability to reach warm Keff >1.0
  - Cold Keff < .993 for 1.5" Comet scram
  - Keff <<<1.0 for all credible configurations during fuel and assembly handling Operational "Requirements"
  - Limit reactivity insertion rates and loading to levels that prevent fuel melting
  - Prevent end-state criticality (with full scram) even if fuel fully melt and reconfigures
  - Limit total possibly reactivity loading to preclude excessive power excursion
  - Limit maximum fuel temperature to <~850 C for "design basis" conditions and transients
  - Reactivity coefficients allow for simple, negative feedback
  - Integral reactivity strong enough for safe/stable operation, but not too large (excess reactivity).
  - BeO reflector with enough worth, while also of a size/geometry to allow affordable fabrication
  - Allow for insertion of heater for non-nuclear testing
  - Allow for placement of variable height B4C rod to simulate flight control rod
  - Allow for vessel to provide vacuum, and also provide a core containment barrier.
  - Allow use of clamps to provide heat-pipe to fuel contract/structure
  - Allow use of multi-layer insulation (mli) to prevent excessive core power loss and substantial heating of vessel.
  - Allow gap/clearance between vessel and moving radial reflector to prevent contact, including thermal expansion effects
  - Prevent contact of uneven-protruding reflector pieces with vessel, and allow reflector to fall in the event of contact.
  - Allow internal gaps to allow for core expansion within vessel, prevent stresses/warping
  - Keep dose rate to room and activation of room similar to Flattop Free Runs and DUFF
  - Keep dose of assembly after warm criticals low enough to allow configuration change within ~week
  - Keep dose in room after full-power test to allow entry to room within ~1 week
  - Keep dose from assembly low enough to allow removal from Comet within ~1 month
  - Keep dose from assembly/components low enough to allow complete disassembly within ~1 year.
  - Size/weight/power requirements of assembly and components must be manageable within the constraints of the facility.
  - All shielding must be affordable, with acceptable dimensions/mass, and allow ample vertical clearance

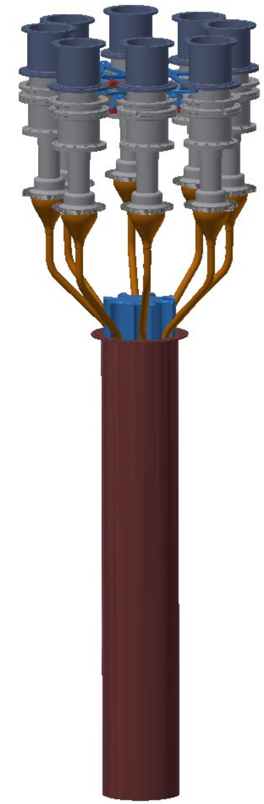
This is not meant to be read, but to make a point – "real" design requires margin, flexibility, and ability to make trade offs amongst a great variety of factors.

Daily trades of performance, cost, schedule, and risk. Design team must be tightly integrated and have the autonomy to make these trades.

1 kWe Versatile Reactor Column Assembly



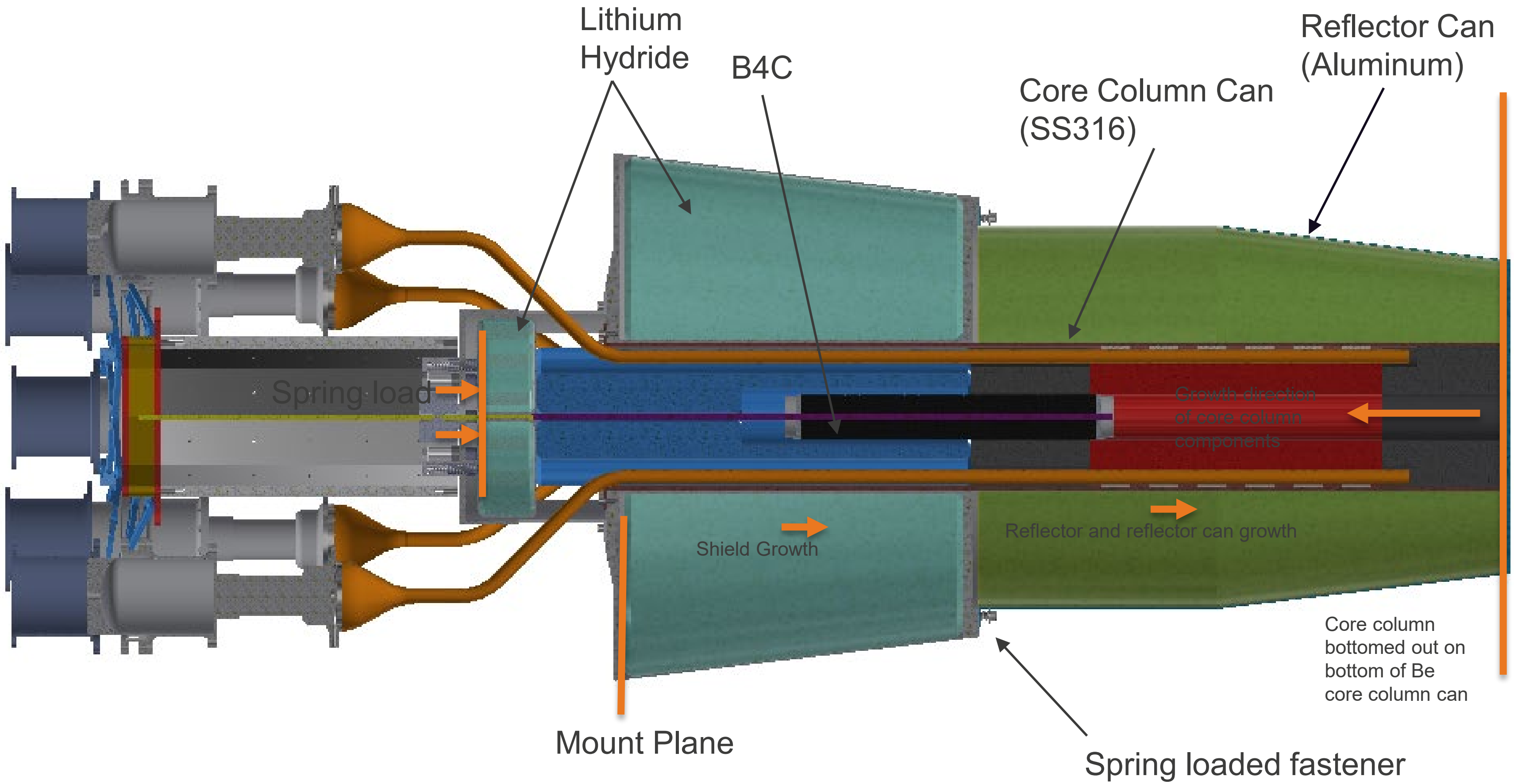




Virtually identical to KRUSTY. Designed to be placed with space or surface power systems

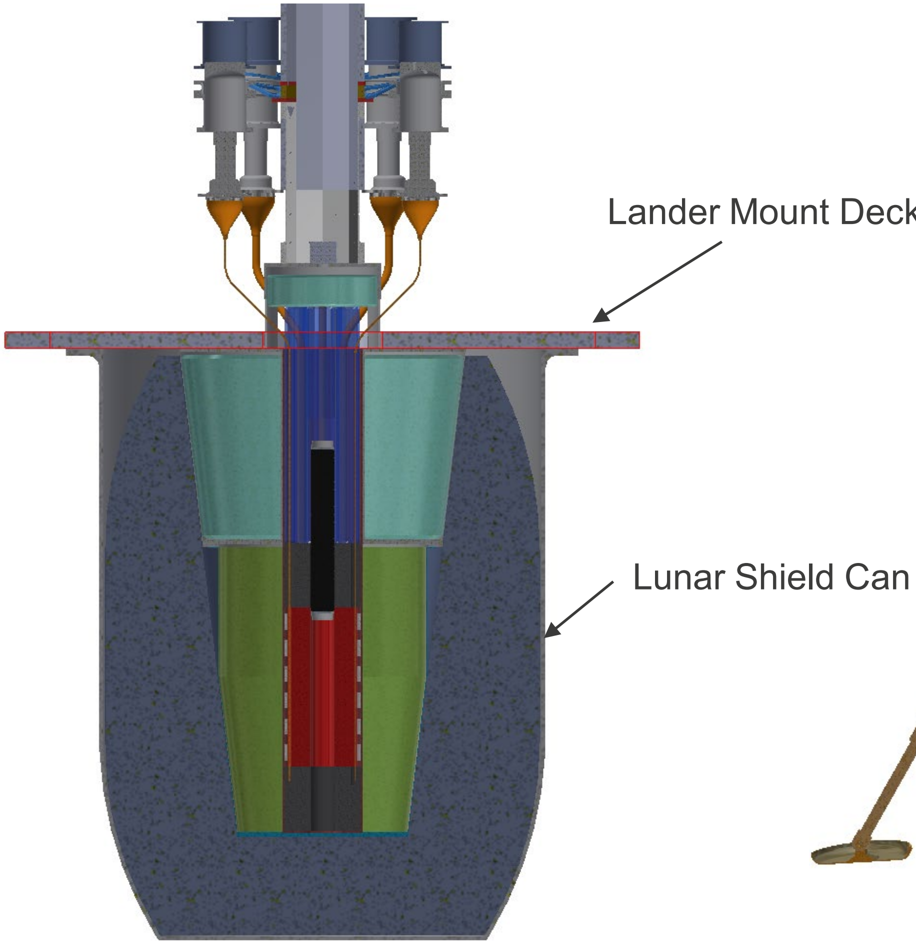
Completed Space Reactor Assembly

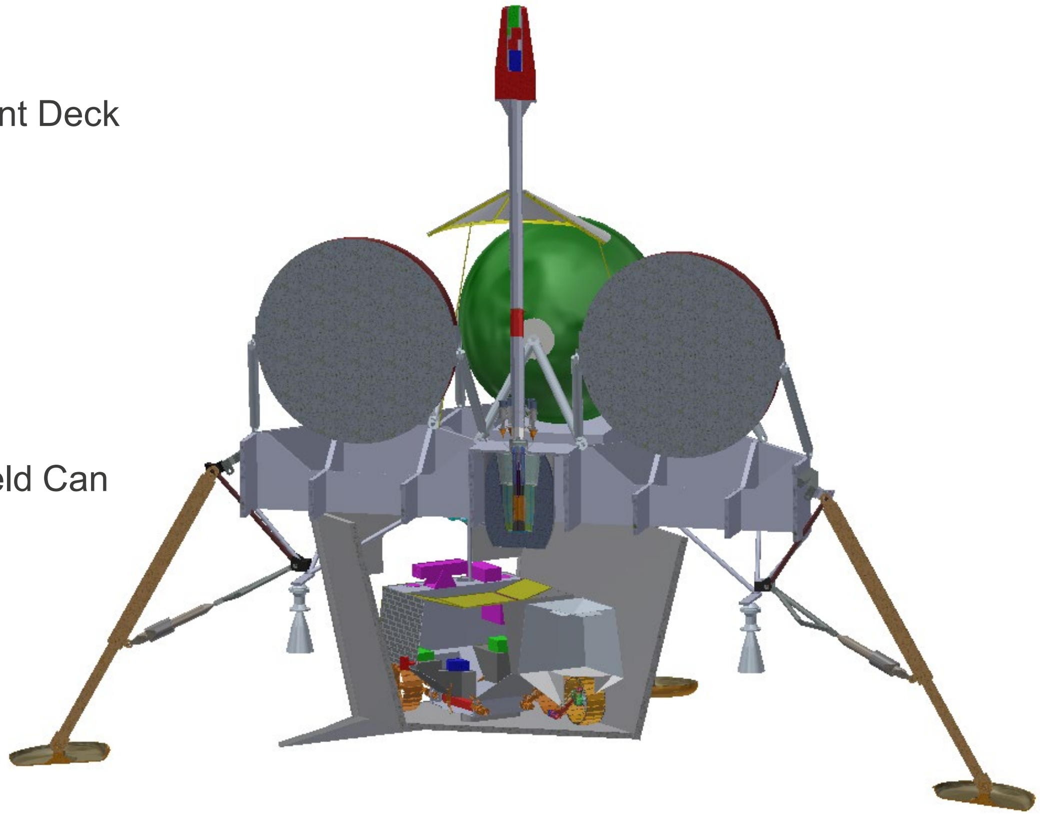
KRUSTY
Fission Power to Enable Space Exploration



Versatile Reactor Column Installation on Lunar Lander

KRUSTY
Fission Power to Enable Space Exploration





High Power Evolution

- **The key aspect of the Kilopower technology that allows simple evolution to higher powers is the simplicity and robustness of system dynamics and control.**
  - The underlying physics and technologies allow this attribute to apply to concepts >>1 MWt, as indicated by the same models that designed and successfully predicted the KRUSTY test.
  - The is true whether the concept uses HEU or LEU, because the physics are still leakage dominated in both cases, and heat transfer is the same.
- **Why is this so important? Because nuclear system dynamics and control is the hardest, most expensive, and riskiest part of space reactor development and testing (due to the difficulty of nuclear-powered testing in today's environment).**
  - Plus, this risk is left unmitigated until the end of the program.
  - More so, testing becomes increasingly difficult as the power level rises, so it is a huge advantage if the operation of a system can be tied to, and potential qualified by, the testing of previous lower-power systems.

High Power Evolution (cont.)

- **There are three major changes in technology that would be needed for Kilopower to evolve to significantly higher power levels.**

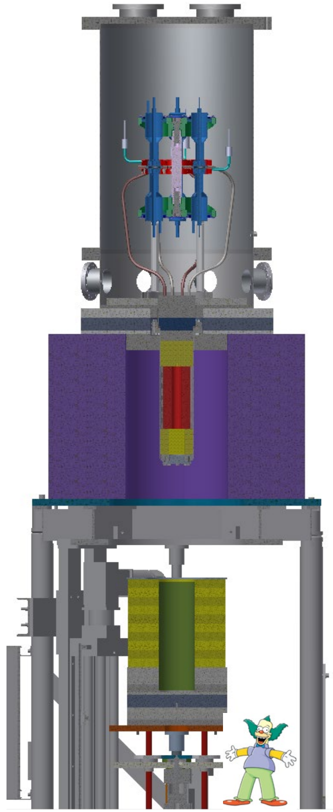
  1) Above 15 HEU to 30 kWe, switch from a solid cast core to a core that contains fuel rods/pellets in a monolithic block (to eliminate the fuel swelling issue – 15 kWe would apply to an HEU core and 30 kWe to HALEU) The block-core reactor dynamics will be the same as the Kilopower core, with thermal expansion providing the only significant feedback effect.
  2) Somewhere between 50 and 100 kWe, change from Stirling to Brayton power conversion. This is a major technology change, but the beauty of the Kilopower load-following approach is that the heat pipes will remove power from the fuel in the same manner.
  3) Somewhere between 1 and 3 MWe (a surface colony or high power NEP), the practicality of a direct-cycle Brayton will trump the advantages of the heat pipe reactor; in this case the coolant flows directly through the holes in the core monolith. The reactor dynamics will still be comparable to Kilopower, including thermal load following, but dynamics will be affected by the changing manner in which power is removed; e.g. the flow velocity, temperature, and pressure.

     Note, a gas-cooled system does not have the option of redundancy, will have more difficulty with decay power removal, significant axial temperature gradient, and is not as amenable to electrical testing. The transition to gas-cooled might be best used after Brayton systems system reliability was proving as part of heat pipe systems.

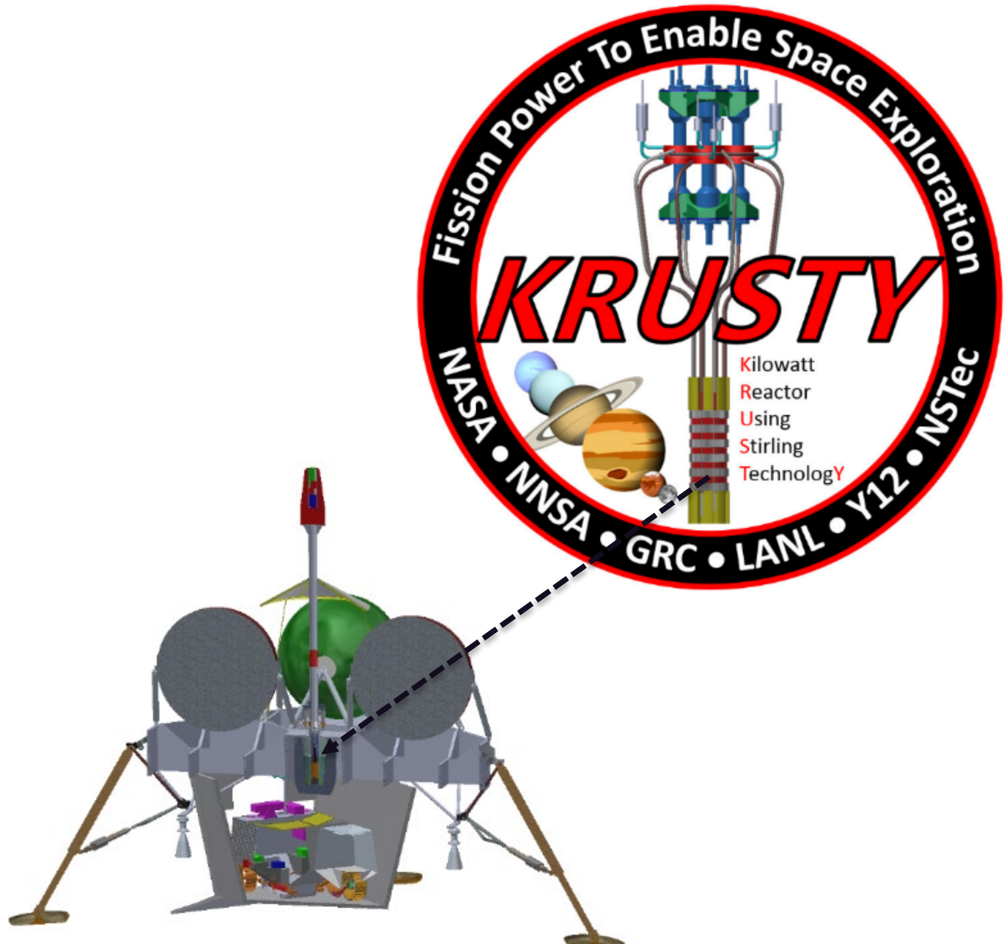
- **The Kilopower design team has spent considerable time investigating these evolutionary concepts, and they look very promising.**
  – The 1 MWe concept is known as MegaPower, and was the precursor to what now are referred to as microreactors.
  – To powers >5 MWe, the idea of a "simple" deployable, launchable fission power system becomes extremely difficult; i.e. the power plant would probably have to be assembled in space or on the intended surface.

Kilowatt Reactor Using Stirling TechnologY = KRUSTY

- **KRUSTY, a prototypic space reactor, was designed, manufactured, tested for <$20M.**
  - The first powered operation of a truly new fission reactor concept in the US in decades.
- **A lot of work is still needed to create a flight system, but the “nuclear” aspects of KRUSTY are very prototypic to a flight system**
  - Nuclear lifetime effects, e.g. irradiation damage and fuel swelling, should not be a problem at the low fluence and burnup (~0.2%).
  - The biggest lifetime concerns for the reactor may be chemical mass transfer between the fuel and heat pipes, and possible creep of the fuel depending on existence of primary stresses.
  - Most of the work required to develop a flight system is non-nuclear: e.g., flight hardware, radiator, Stirling convertors, startup-rod system, launch approval, launch loads, flight qualification, lifetime effects, spacecraft integration.
- **Keys to success:**
  - Integrated Simplicity! Following the simplest path through design, development, fabrication, safety, and testing.
  - Best is the enemy of good enough.
  - Small tightly-integrated team of people dedicated to the project.
  - Management left project decisions to technical team – not just technical trades, but where money was best spent and the daily ability to a) further study an issue or b) make a command decision.
  - NASA/NNSA allowed a seamless interagency team. NSSA recognized NASA as the customer, and NASA trusted that NNSA would make sure nuclear operations were done legally and safely.
  - Integrate the regulators, simplify their job, and keep them well informed.



Backup Slides



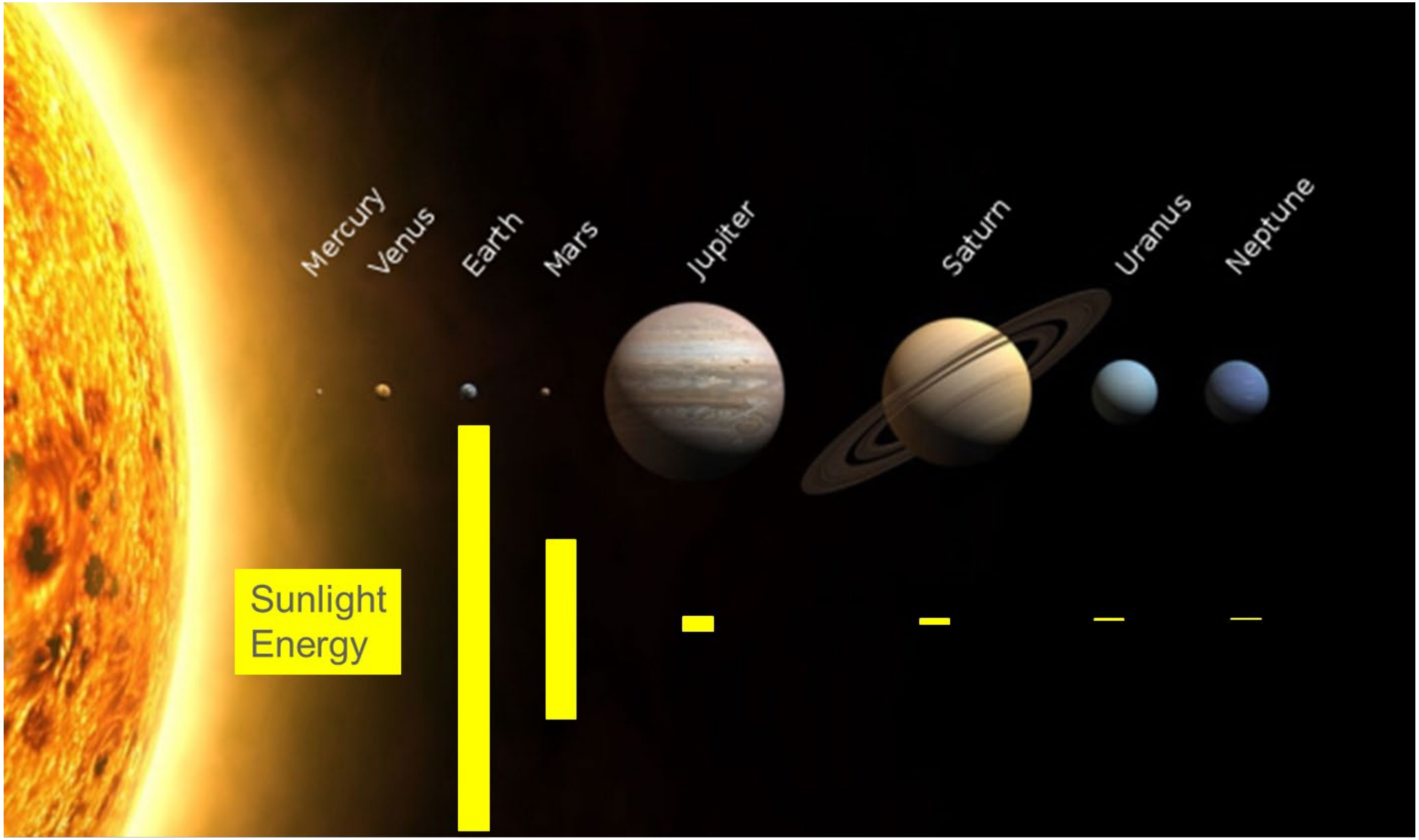
Fission is a Well-Developed, Extensively Utilized Technology – but has been stagnate for 40+ years

- 1938: Fission discovered by Han and Strassmann
- 1942: First fission reactor: Fermi's Chicago Pile
- 1951: First power nuclear power plant: EBR1 Idaho
- 1956: First commercial power plant: Calder Hall, England

- '60s and early '70s: hundreds of nuclear reactors built and deployed for power generation, research and military uses.

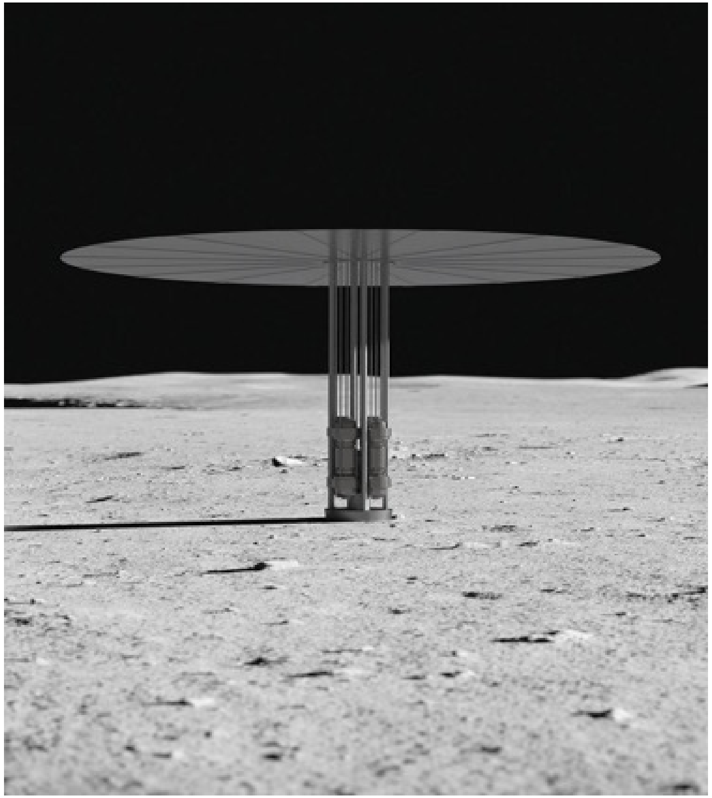
- 1977: Last new reactor built in US
  - (other than 2 cookie-cutter Triga research reactors in the early '90s)

Solar Power in the Solar System



Challenges for Solar Power on Surface

- **Mars surface presents major challenges**
  - 1/3rd solar flux of Earth
  - Greater than 12 hour nights (need batteries)
  - Variations in solar energy by geography
  - Long-term dust storms (years in length)
- **The Moon is even more challenging**
  - 14 days of darkness
  - huge temperature swings, to extremely cold temperatures
  - power needed in permanently shaded craters to extract water ice.

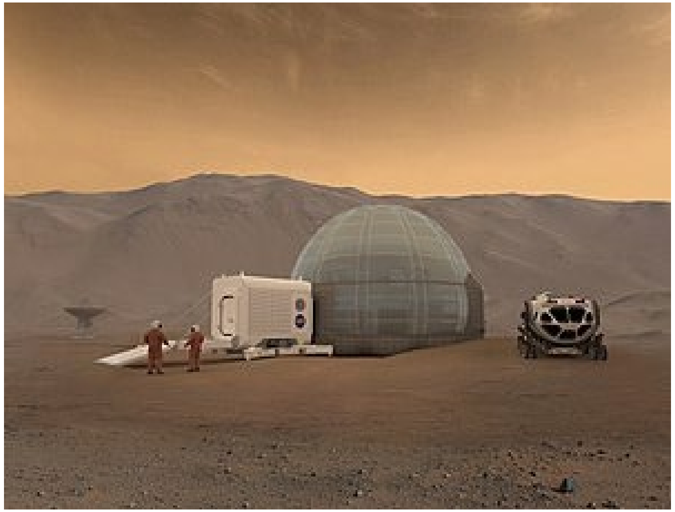


NASA rendition of a Kilopower reactor on the Moon

What is needed for Humans to go to Mars

- **Electricity would be used to make:**
  - Propellant to get back to Mars orbit
    - Liquid Oxygen
    - Methane

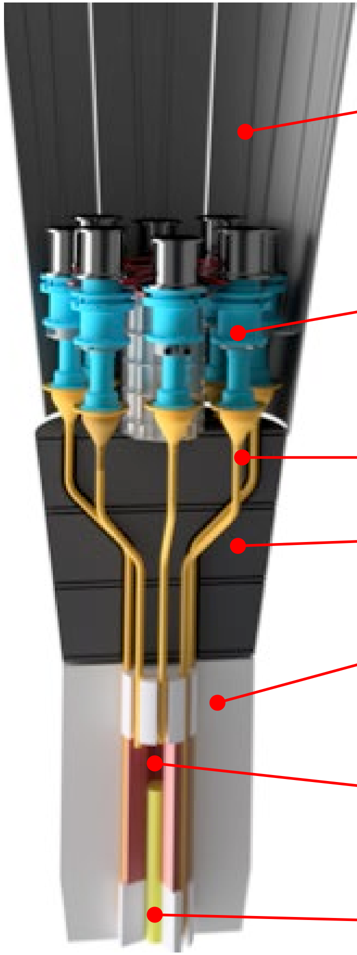
International Mars Research Station – Shaun Moss



Mars Base Camp – NASA Langley

- **Electricity is needed for:**
  - Oxygen, water, etc. for astronauts
  - Power for habitats and rovers
  - Drilling, melting, heating, refrigeration, sample collection, material processing, manufacturing, video, radar, telecomm, etc.

Basic 1-kWe Kilopower Concept and Actual KRUSTY Components



Titanium Heat Pipe Radiator

Stirling Power Conversion System

Sodium Heat Pipes

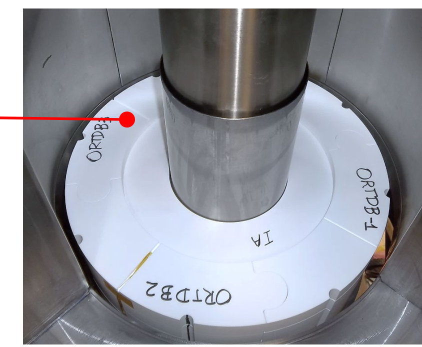
Lithium Hydride, Tungsten Shielding

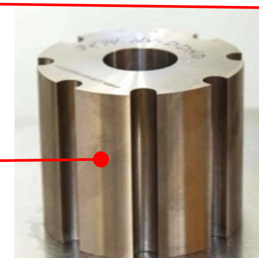
Beryllium Oxide Neutron Reflector

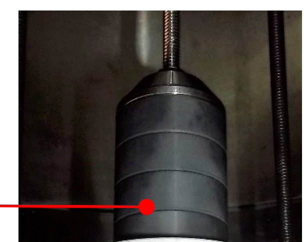
HEU U-Mo Cast Metal Fuel

B_4C Neutron Absorber Rod

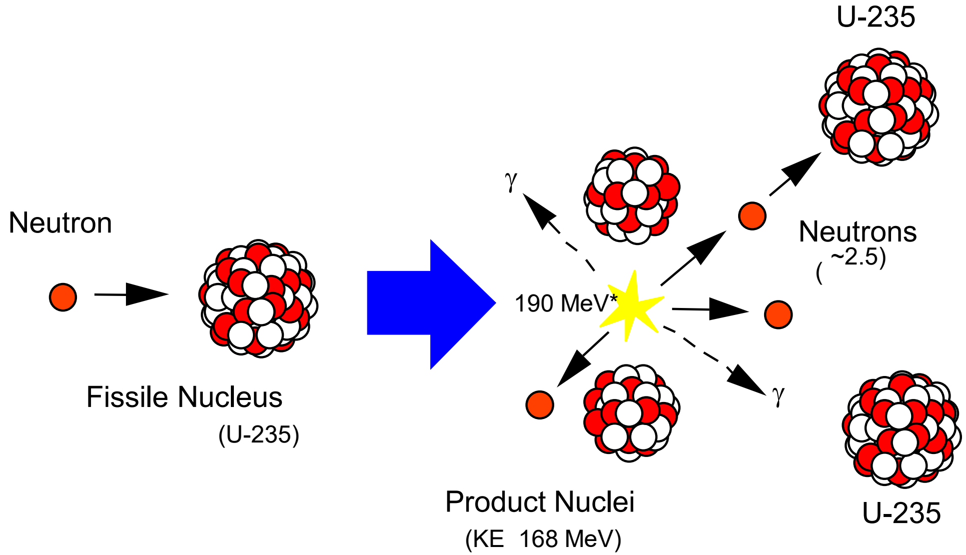
System enclosed in vacuum







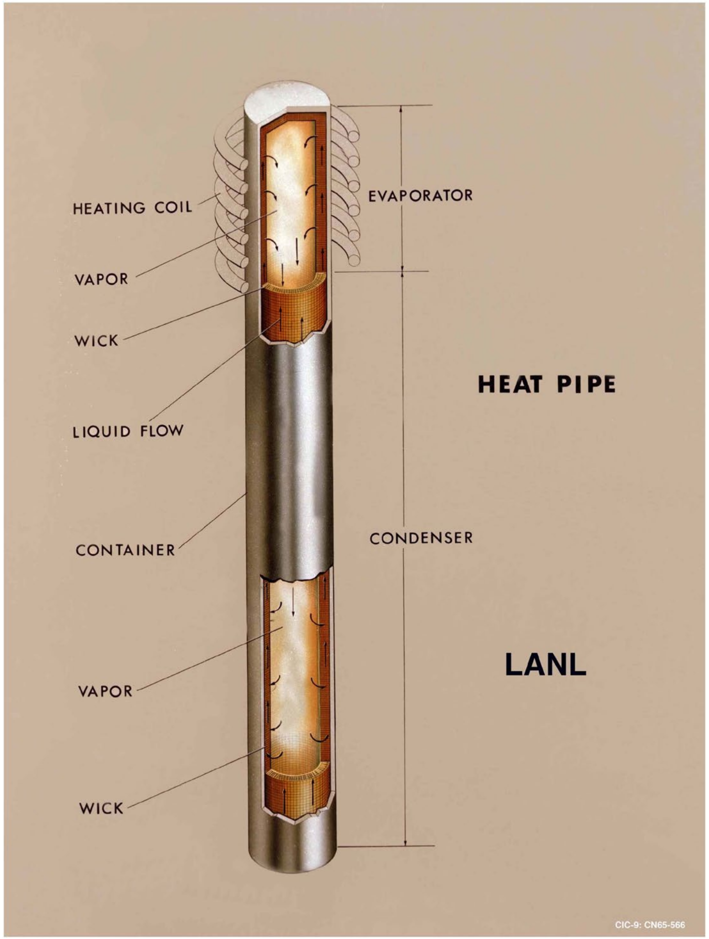
1) Nuclear Fission Creates Power



The majority of energy is deposited where the fission occurs within the uranium fuel.

2) Heat Pipes Transport the Power

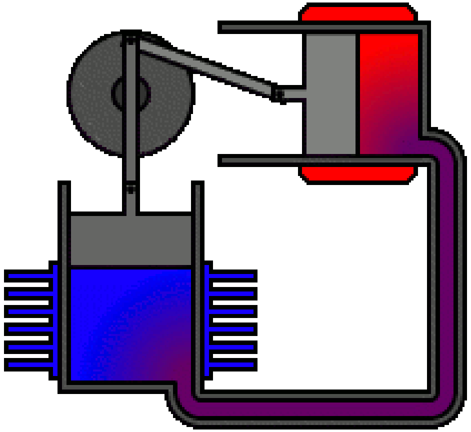
- A heat pipe is a sealed tube with a small amount of liquid that boils at the hot end, the vapor travels to the cold end where it condenses back to a liquid.
- A wick is used to bring the fluid back to the hot end
- A heat pipe works in any direction - even against gravity
- Heat pipe are a very efficient way to move heat



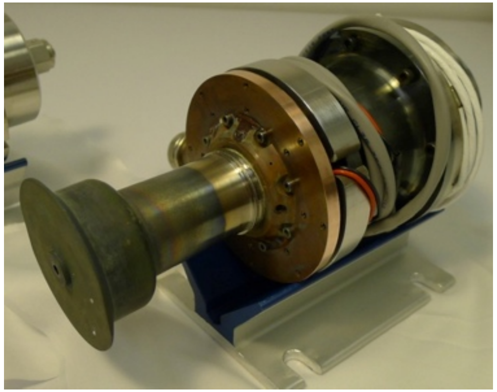
3) Stirling Convertor Creates Electrical Power

- A Stirling engine is a heat engine that turns heat into mechanical motion
- An alternator creates electricity from the mechanical motions.

Reverend Dr. Robert Stirling
Wikipedia commons



Wikipedia commons



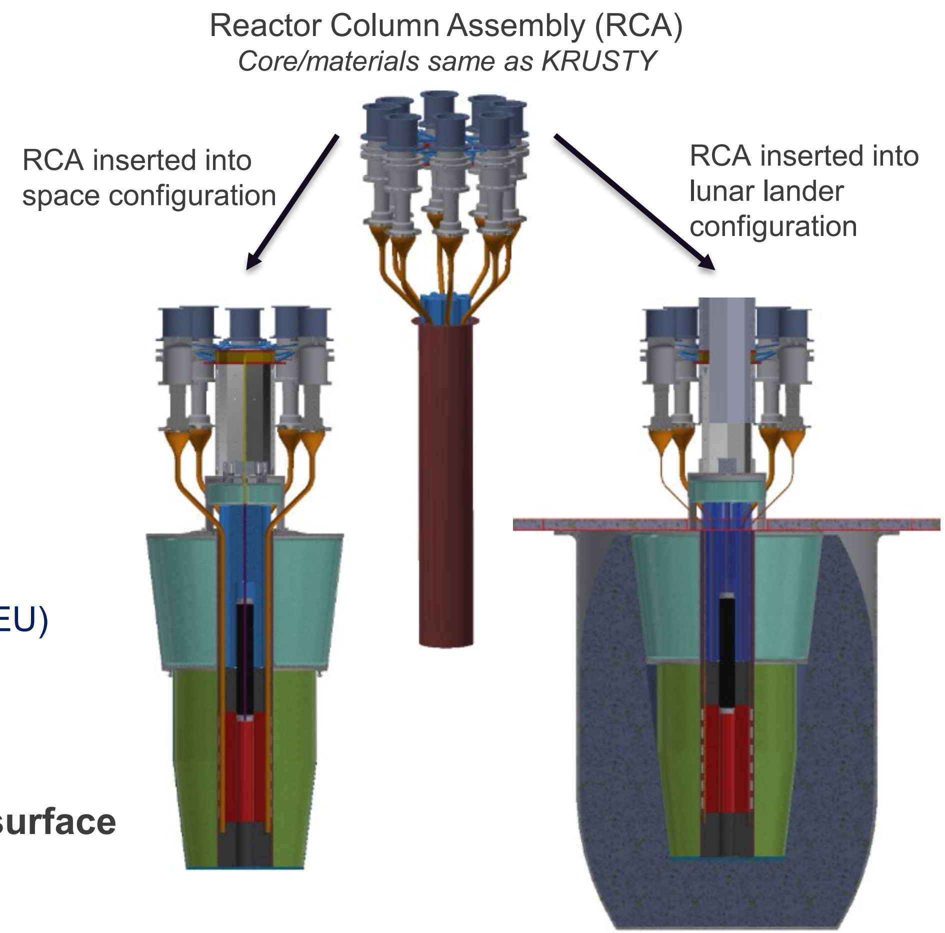
Modern Stirling Engine

Current Kilopower Design Concepts

KRUSTY

Fission Power to Enable Space Exploration

- **Concepts evaluated**
  - 1-kWe Lunar surface demo – primary focus
  - 1-kWe space power – for space science
  - 10-kWe space power – for NEP
  - 10-kWe Mars surface demo – for ISRU mission
  - Cluster of four 10-kWe reactors – for Human mission
  - Evolutionary concepts up to 1 MWe.
- **Options evaluated for each concept**
  - HEU vs LEU
  - Tight vs Relaxed dose requirements
- **Each reactor concept rooted in KRUSTY**
  - KRUSTY fuel spec – U7.65Mo at 98.5% TD (LEU or HEU)
  - Haynes-230/Na HPs
  - BeO radial and axial reflectors
  - B4C control drum poison
- **Same "root" reactor power system for space and surface**
  - Only significant changes are in radiator and shielding



Kilopower / KRUSTY Differences

differences for reactor only

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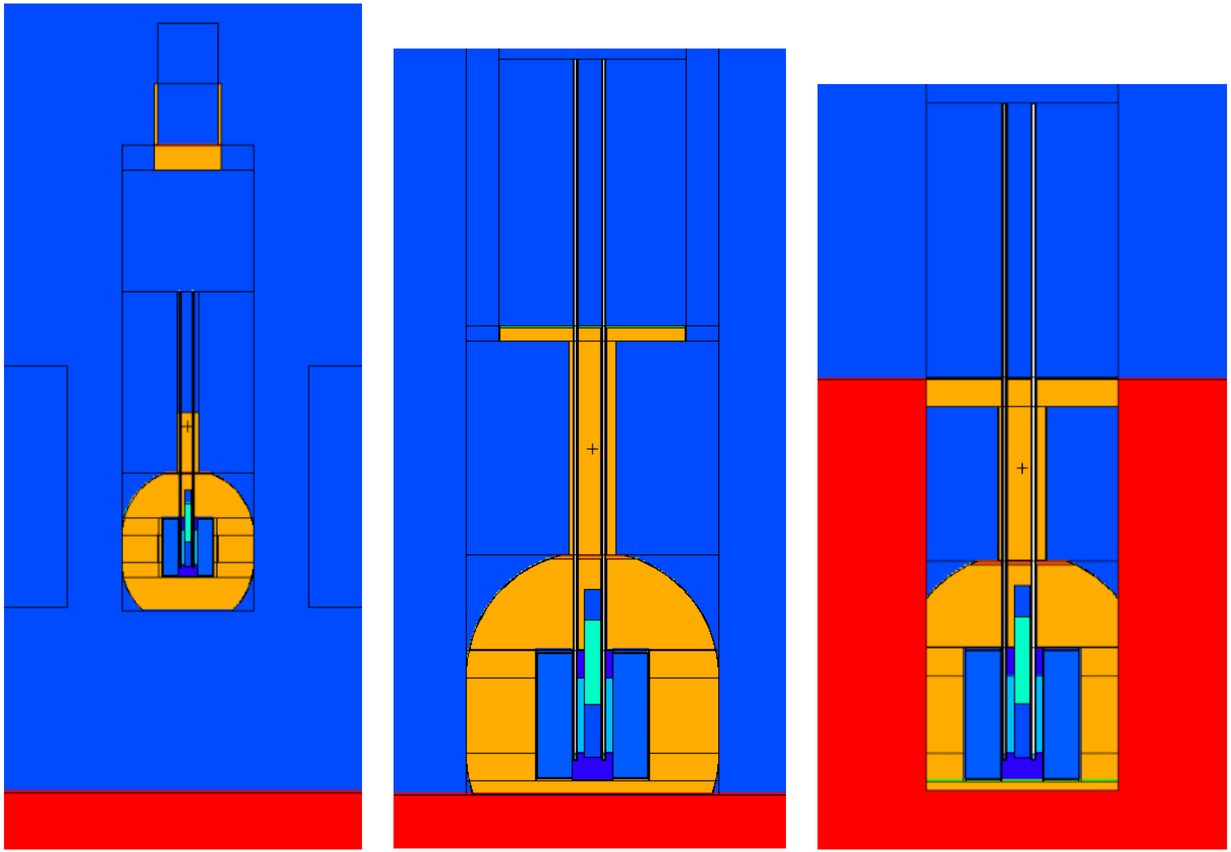
	Space 1-kWe Kilopower	KRUSTY	Mars 10-kWe Kilopower
Reactivity Control	Central poison rod	Comet lifts reflector	Central poison rod
Operating time	15 years	28 hours	12 years
Lifetime Reactivity Control	No	n/a	Yes
Fuel/radref separation	1-mm	1-cm (the Divide)	1-mm
Core can/vessel	Maybe	Yes	Yes
Reference heat pipe OD	1/2"	1/2"	5/8”
Heat pipe thermal bonding	Clamp force?	Clamp force	Braze or Diffusion Bond
U235 mass	28.4 kg	28.0 kg	43.7 kg
Core Length	24 cm	25 cm	28 cm
Shielding	LiH/DU shadow	SS/B4C 4pi	SS/B4C 4pi
Radref temperature	~700 K	~400 K	~700 K
Gravity	0g	1g	.38g
Space Qualification	Yes	No	yes
Launch safety/approval	Yes	No	yes

Various Mars Shielding Configurations



Kept on lander — Placed on surface — Buried

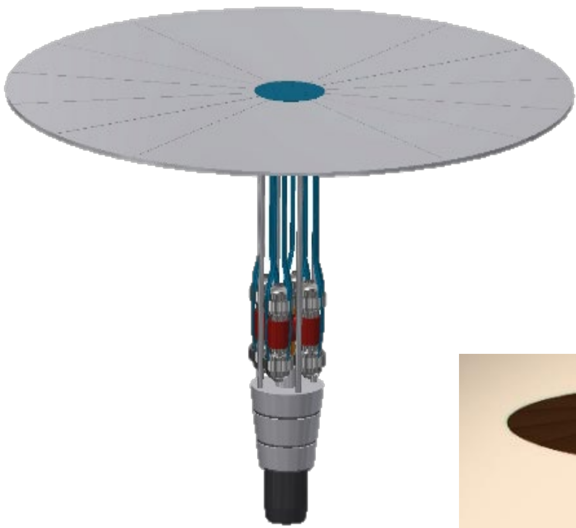
Of course the best option would be to choose sites with a ridge, crater lip, or other topographic feature between the reactor and the human outpost.

Creating berms, filling sandbags or structures with regolith is also very effective if the architecture allows it.

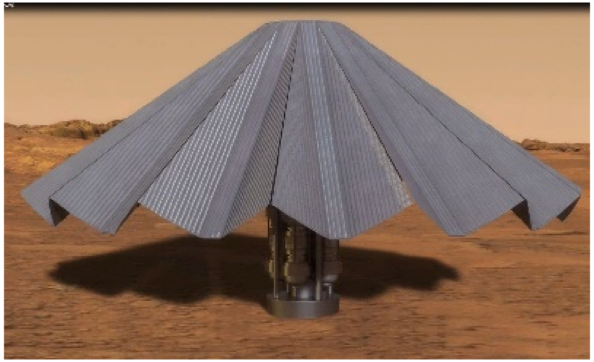
In general, 1 m of regolith that blocks the line of site between the reactor and outpost will effectively eliminate reactor radiation.

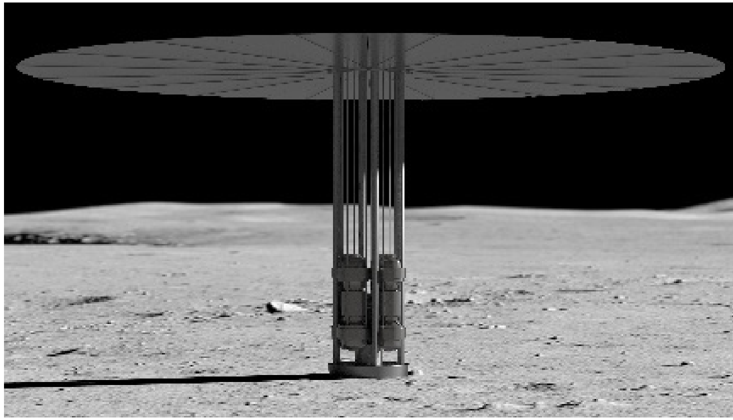
Line-of-site shielding options above are ideal on the Moon, but on Mars sky-shine is remarkably a significant factor, so some ~4pi shielding is still required.

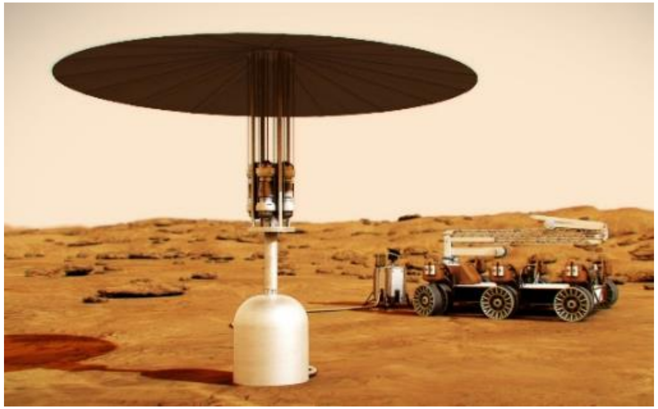
Deployment of Kilopower Surface Reactors



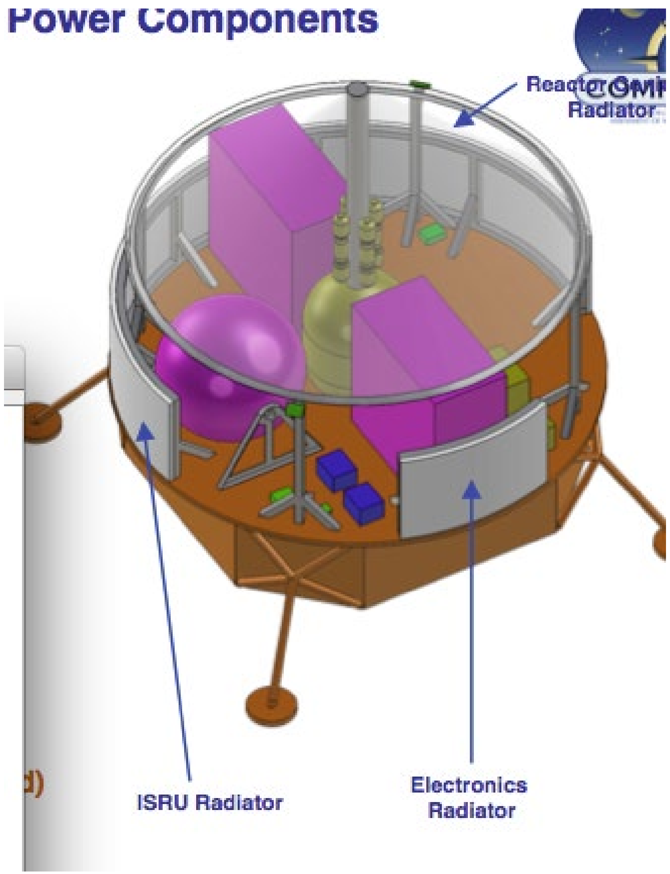
10 kWe
1500 kg

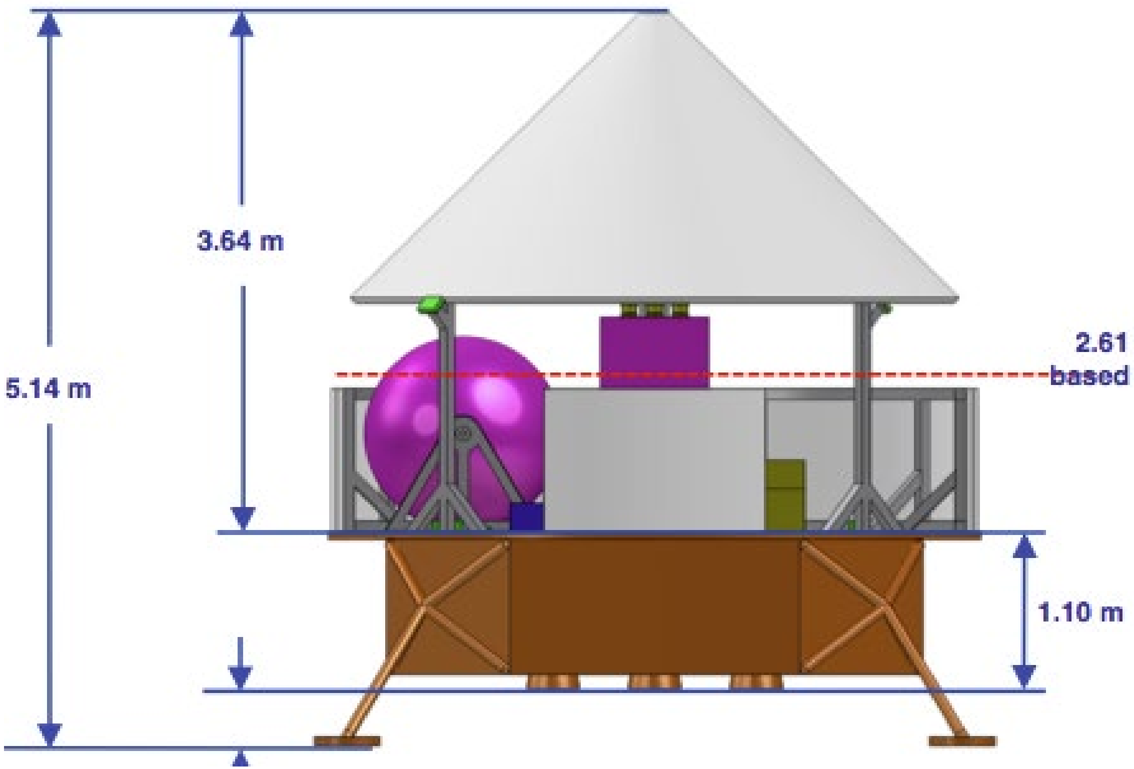






10 kWe Mars ISRU Demo Proposal





Example of Approachability – Dose from buried FSP after shutdown standing next to the power system.

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Dose Rate After Shutdown (rem/hr) - 1 meter from Reactor C/L						
	Reactor Full Power Operating Time					
Time After Shutdown	1 Minute	1 Hour	1 Day	1 Month	1 Year	8 Years
100 sec. (1.7 min)	1.2E-01 *Rego 65%*	6.2E-01 *Rego 54%*	8.8E-01 *Rego 63%*	3.7E+00 *NaK 79%*	3.7E+00 *NaK 79%*	3.7E+00 *NaK 79%*
1e3 sec. (17 min)	5.4E-03 *NaK 40%*	2.2E-01 *NaK 59%*	4.5E-01 *Rego 59%*	3.2E+00 *NaK 89%*	3.2E+00 *NaK 89%*	3.2E+00 *NaK 89%*
1e4 sec. (~3 hours)	2.6E-03 *NaK 76%*	1.5E-01 *NaK 78%*	2.9E-01 *Rego 54%*	2.8E+00 *NaK 92%*	2.8E+00 *NaK 92%*	2.8E+00 *NaK 92%*
1e5 sec. (~1 day)	6.4E-04 *NaK 97%*	3.8E-02 *NaK 97%*	5.3E-02 *NaK 69%*	8.3E-01 *NaK 96%*	8.4E-01 *NaK 96%*	8.4E-01 *NaK 96%*
1e6 sec. (~2 weeks)	2.3E-07 *Rego 67%*	4.2E-06 *Fuel 70%*	9.1E-05 *Fuel 80%*	1.5E-03 *Fuel 72%*	2.7E-03 *Fuel 47%*	4.4E-03 *In718 39%*
1e7 sec. (~4 months)	1.6E-07 *Rego 89%*	3.5E-07 *Rego 73%*	4.6E-06 *Rego 66%*	1.2E-04 *Rego 59%*	6.8E-04 *In718 46%*	2.2E-03 *In718 74%*
1e8 sec. (~3 years)	1.6E-07 *Rego 89%*	1.9E-07 *Rego 74%*	8.1E-07 *In718 77%*	2.4E-05 *In718 76%*	2.7E-04 *In718 78%*	1.3E-03 *In718 87%*

>10 rem/hr	>1 rem/hr	>100 mrem/hr	>10 mrem/hr	<10 mrem/hr	< 1 mrem/hr	<0.1 mrem/hr
lifesaving only	mission critical ops?	maintanence ops?	>lunar background	<lunar background	negligible	Earth background

Notes: a) An unburied system will provide significantly greater doses from activated material (maybe order of magnitude depending on lots of factors). b) The 4-times lower power of Kilopower will provide ~linear reduction (provided units are >~5 m apart). c) The NaK source will not be present in Kilopower (small amount of Na in heat pipes, but negligible in comparison.

Mars Architecture Summary
Four 10-kWe Kilopower Units

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	Total Shield (kg)	Ave. Unit Shield (kg)	Instrument Distance (m)	Human Distance (m)	Low-Volt PMAD (kg)	Electric Power (We)	Total Mass (kg)	Specific Power (We/kg)
Placed on Surface	2022	506	140	2000	1865	33.5	7587	4.4
Left on Lander	2424	606	160	2000	1865	33.5	7989	4.2
Bermed/Topographic	1952	488	~50	~500	700	38.0	6352	6.0
Buried 75-cm-deep hole	1600	400	~25	~200	600	38.5	5900	6.5
Buried 150-cm-deep hole	1248	312	10	80	500	38.8	5448	7.1

Human distance is where they can live, they can approach substantially closer if needed during EVAs.

The specific power will go up slightly with increased number of units and vice versa.

On-lander mass could be reduced if lander components/materials could be positioned to serve as shielding

Approximate (tilde) cases were not calculated - they are based on previous studies.

At some distance, high voltage transmission would make sense, perhaps better option if 2 km separation is used.

Development risks need to be put in perspective when programs are being considered.

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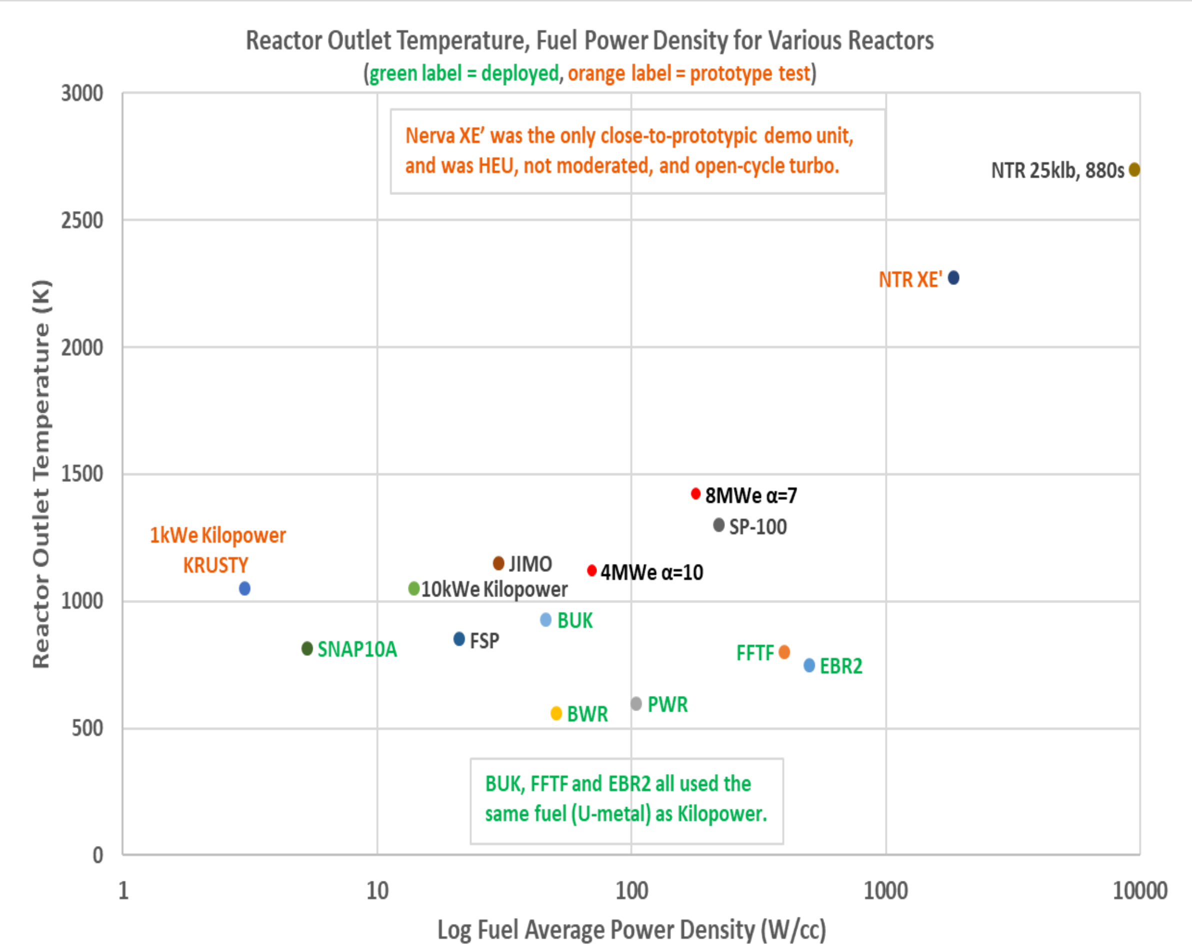
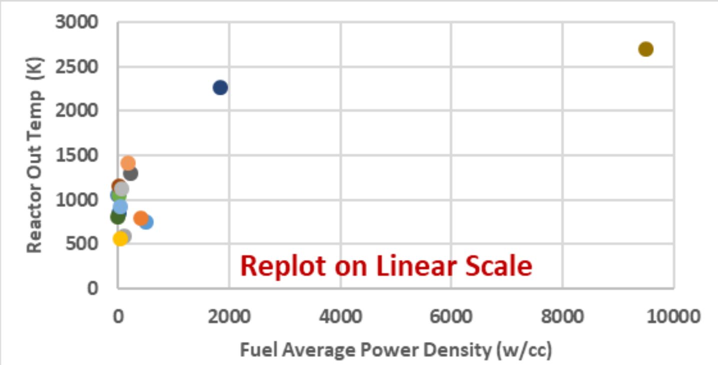


Biggest Reactor Development Risks

– Neutronic and dynamic complexity
– Reactor "outlet" temperature
– Power density
– Lifetime (if high power density)

The above are in general order of importance, and can vary by concept. There are dozens of risks, but most are a strong function of the above (e.g. adiabatic heat-up rate, power, fluence, chemistry, burnup, etc.)

Neutronic/dynamic complexity is listed as #1 because nuclear system dynamics/control is generally the hardest, most expensive, and riskiest part of space reactor development (due to the difficulty of nuclear-powered testing in today's environment)



High-Level Estimates of Technical Risk for Power and Propulsion Reactors

------ 7 year full power lifetime kilopower derived reactor power systems (masses based on shield for space application) --------										
	Power	Mass	T-hot	alpha		Technical Risk			Odds of Technical Success	
	MWe	mT	K	kg/kWe	1st Flight	Flight evolve	GNT evolve	1st Flight	Flight evolve	GNT evolve
Kpow Gen0	0.001	0.5	1000	500	KRUSTY	KRUSTY	KRUSTY	0.99	0.99	0.99
Kpow Gen1	0.01	2	1000	200	extremely low	extremely low	extremely low	0.98	0.98	0.98
Kpow Gen2	0.1	5	1000	50	somewhat low	very low	extremely low	0.84	0.94	0.96
Kpow Gen3	0.5	12.5	1000	25	modest	very low	skip	0.75	0.90	0.96
Kpow Gen4	2	30	1000	15	somewhat high	very low	extremely low	0.65	0.87	0.94
MMW Gen1	4	40	1150	10	high	very low	extremely low	0.50	0.83	0.92
MMW Gen2	8	56	1400	7	very high	modest	low	0.25	0.62	0.85
MMW Gen3	12	60	1700	5	extremely high	high	modest	0.10	0.31	0.64
MMW Gen4	20	60	1900	3	insane	very high	high	0.01	0.08	0.32
------- 10 hour full power lifetime unmoderated NTR systems --										
	Power	Thrust	T-hot	Isp		Technical Risk			Odds of Technical Success	
	MWt	klb	K	sec	1st Flight	Flight evolve	GNT evolve	1st Flight	Flight evolve	GNT evolve
NTP FD1	1	0.1	1000	500	very low	very low	extremely low	0.96	0.96	0.98
NTP FD2	15	1	2040	750	modest	low	skip	0.75	0.88	0.98
NTP Gen1	220	12.5	2260	800	high	somewhat low	somewhat low	0.50	0.74	0.82
NTP Gen2	500	25	2510	850	very high	somewhat low	skip	0.25	0.62	0.82
NTP Gen3	500	25	2740	900	extremely high	modest	modest	0.10	0.47	0.62
NTP Gen4	500	25	3000	960	Insane	very high	high	0.01	0.12	0.31
------ 10 hour full power lifetime moderated NTR systems (much lower fuel mass) --										
NTP FD1	1	0.1	1000	500	modest	modest	somewhat low	0.75	0.75	0.84
NTP FD2	15	1	2040	750	very high	high	skip	0.25	0.38	0.84
NTP Gen1	220	12.5	2260	800	extremely high	high	somewhat high	0.10	0.19	0.55
NTP Gen2	500	25	2510	850	Insane	extremely high	skip	0.01	0.02	0.55
NTP Gen3	500	25	2740	900	Insane	insane	somewhat high	0.01	0.00	0.35
NTP Gen4	500	25	3000	960	Insane	insane	very high	0.01	0.00	0.09

same reactor

GNT = ground nuclear test
Better chance to learn than flight test, but much more expensive and time consuming, especially for NTP.

More components and long lifetime, but good ability to electrically test (Kilopower great, MMW decent), largely decoupled Rx and PCS testing and development, and simple system dynamics

Cannot be electrical tested and extremely high temps and power, but benefit from simple system dynamics, fewer components and shorter lifetime. GNTs are more difficult and expensive.

Cannot be electrical tested, extremely high temps and power, and complex dynamics, but benefit from fewer components and shorter lifetime. GNTs are the most difficult/risky/expensive.

Technologies for advanced generations (fuels, turbomachinery, radiators, EP) can and should be pursued prior to their system development.

Space Reactor Safety

- **A reactor that has not undergone fission, (been turned on), has very very low safety concerns. It will have from 1 to 10's of curies of naturally occurring radioactivity**
  - This is 1,000s to 10,000s times lower radioactivity than in current radioisotope systems already flown in space
- **Full aerosolation of the core will have consequences <u>100's of times less</u> than background radiation at site boundary.**
- **After the reactor has fissioned, it will become radioactive**
  - Reactors would only be used in deep space, very high Earth orbit (long term decay) and on other planets.
- **Kilopower is designed to preclude inadvertent criticality during any feasible accident.**
  - Reactor remains subcritical immersed in water, surrounded by sand, or during any feasible compaction, launch pad fire, etc.
- **For human missions, once on planetary surface (or anywhere in space), reliability is far more important to astronauts than "traditional" nuclear safety (i.e., the potential release of radioactivity into the environment).**

Space Fission Power -- Bottom Line

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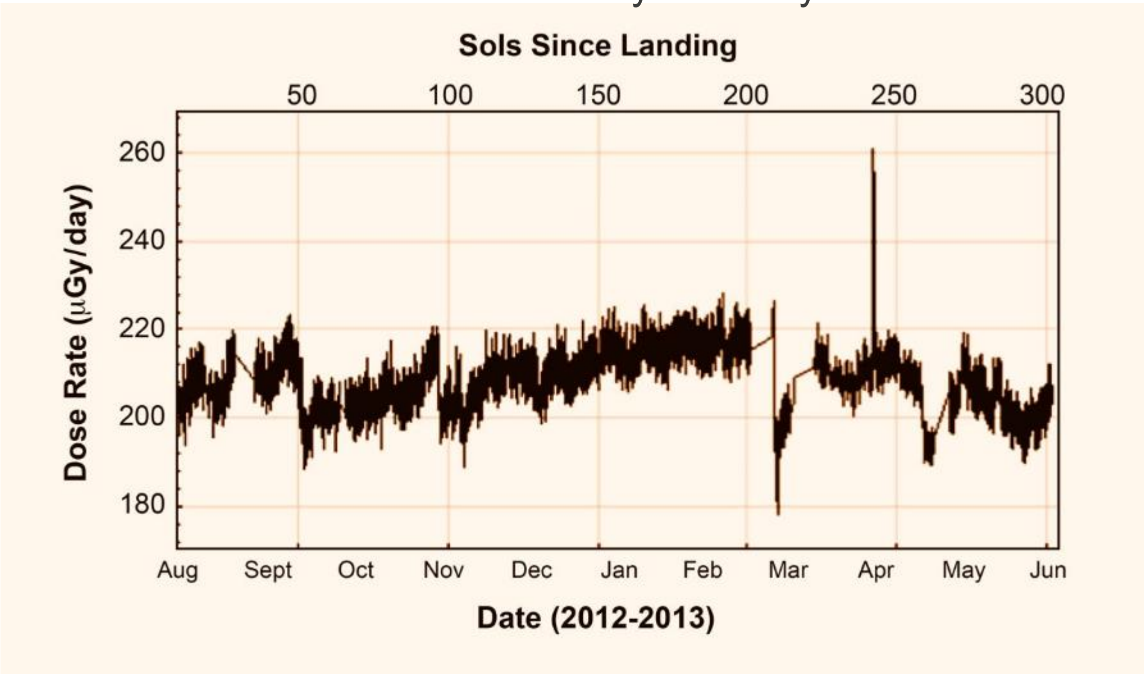
- **KRUSTY and Kilopower have shown that space reactor development is not inherently expensive or lengthy.**
  - $18M for 3 years to design, build and test a prototypic 1-kWe fission power system.
    - The first nuclear test of a new space reactor system in over 50 years!
- **We need to continue to take manageable steps (cost and schedule) to evolve fission power and propulsion systems.**
  - Kilopower technology is now available to provide surface power for small human outposts.
  - The path is reasonably simple to get Megawatt power systems on the surface on Moon and Mars.
- **Human propulsion will require several development steps**
  - Starting from scratch, a 900-s-Isp, 25-klb NTP and 10-MW, 5-kg/kWe NEP would be ~equally difficult.
    - Very little of ROVER/NERVA experience applies to the proposed high-performance NTP systems.
  - However, NEP systems can benefit greatly from the development of surface power systems (and SEP systems) and are easier to test and evolve, such that the NEP power system should ultimately be easier.
    - Additionally, NEP systems have lots of headroom to improve, while NTP is close to its realistic limit at 900 sec.

Background Dose on Mars

Dose observed by Curiosity



"The RAD surface radiation data show an average GCR dose equivalent rate of 0.67 millisieverts per day from August 2012 to June 2013 on the Martian surface." = 3 mRem/hr

"In comparison, RAD data show an average GCR dose equivalent rate of 1.8 millisieverts per day on the journey to Mars, when RAD measured the radiation inside the spaceship."

A Trip to Mars Reduces Astronaut Cancer Risk

- Current estimates are that the dose received during a modestly shielded (with solar-storm shelter) 3-year Mars mission would be ~1 Sievert (100 Rem)
- The traditional (linear-no-threshold) model suggests that this mission radiation will create a 5% chance of developing fatal cancer; however this model regarded by most experts as highly conservative and counter to actual data.
- Also, it should be noted that cancer becomes less fatal every year – recent years have shown survivability increase by several percent per year, so by the time we launch and return an astronaut from Mars the cancer mortality rate should be lower.
- If we consider the conservatism of no-threshold model, and decreasing cancer morbidity, it is reasonable, and I think very conservative to place chance of death ultimately caused to mission radiation at 3% (whereas if I had to bet I'd say it is more likely <1% than >1%)
- This presumed 3% chance of premature death is likely late in life, and extremely likely to be after an astronaut has obtained hero status and completed an achievement worthy of their life – any true explorer would be absolutely thrilled with this outcome.

A Trip to Mars Reduces Astronaut Cancer Risk

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Fission Power to Enable Space Exploration

- **Still, NASA appears very worried about the chance of radiation killing an astronaut.**
- **First, this stance is pathetic. Our society has benefited greatly because people explored the world with a huge risk of malaria, scurvy, shipwreck, etc. <u>To impede the progress of humankind because of a 3% chance of death shows no respect for future generations, especially since there would be millions of individuals gladly willing to take that risk.</u>**
- **Second, a mission to Mars would likely "save" an astronaut from dying from cancer. The problem is that this 3% increase in fatal cancer assumes that there is zero risk of killing the astronaut "prematurely" during the mission.**
  - A highly utilized spacecraft, the Space Shuttle, performing a relatively simple mission killed >1% of astronauts.
  - On a Mission to Mars astronauts can die acutely via: launch, Mars trajectory burns, Mars capture, landing, ascent, docking, Earth-return burns, Earth arrival and landing. That's at least 8 distinct risk points that each would extremely hard to get below 1%, and realistically should average 2 or 3% each for practical, initial missions.
    - Actually, if we develop a new advanced technology to shorten trip time, their failure rates will likely be higher than chemical prop.
  - Furthermore, at any time during the mission there are a slew of risks, most notably loss of power supply, life support, vessel/space suit integrity, fire, etc. Not to mention risks due to human error by crew members or ground personnel, plus a chance of an illness, medical emergency that could have been survivable in an ER on Earth, but not in space.
  - <u>A reasonable target for the chance of death for early round-trip missions might be 25%,</u> although it will be hard to achieve and most true explorers would gladly accept a higher risk.

A Trip to Mars Reduces Astronaut Cancer Risk

- **To close this point… A US citizen has ~25% chance of dying from cancer. If we assume a 20% chance of acute mission-induced death (which is low, based on previous slide), the chances of a Mars astronaut dying from cancer is (1.0-0.2)*((25+3)/(100+3)) = 22% as compared to the 25% of dying from cancer if he/she stayed home.**

- **Of course this is really not the point – it's a paradoxical (o.k. asinine) way of making bigger points.**
  - Radiation is a minor risk compared to other mission risks.
  - Like our predecessors we need to focus on the great things we could do for ourselves and future generations -- if we try to exhaust every possible risk (especially relatively minor ones like space radiation), we will never achieve anything great.

Chernobyl Facts

vs HBO series fear-mongering

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- There were 134 documented emergency first responders with high exposure: 29 first responders died within months from Acute Radiation Sickness (ARS), >>100 Rem of acute exposure.
  - There were 19 fatalities among this group over the next 20 years, which was within the expected morbidity range of this group (so no significant radiation effect).
- There were 9 thyroid cancer deaths of children in the surrounding region, which was significantly higher than the expected number for the population, so radiation likely was the cause for some of them.
- None of the 3 “suicide” squad guys sent to open the valves under the reactor died from radiation
  - 1 died from heart attack and the other 2 are alive today.
- The “sacrificial” troops sent to clear off the roof actually got doses within the traditional standards for rad workers, which has not been shown to increase cancer risk, nor has there been any evidence that it has for them.
- There has been no demonstrated statistical increase in cancer mortality with the public in surrounding areas (except for the aforementioned 9 deaths)
  - This is remarkable because so many people have been looking hard find a correlation for decades (usually when people are looking for some sort of statistical anomaly they will find it).
- From the comprehensive 2006 World Health Organization (WHO) report – “The recent morbidity and mortality studies of both emergency workers and populations of areas contaminated with radionuclides in Belarus, Russia and Ukraine do not contradict pre-Chernobyl scientific data and models”;
  - i.e. no statistical evidence of increase deaths in this population (which would have been seen if radiation had caused hundreds of cancer deaths for people who had lived near Chernobyl).

Chernobyl Facts

actual deaths not remotely close to predictions

- HBO declares "most estimates range from 4,000 to 93,000 deaths", but the scientific data thus far completely debunks this, and the final tally will very likely be <100.
- The low end of the HBO range, 4,000 deaths, was indeed in the range of the "scientific" estimations made in 1986, some of which were included in the 2006 WHO report (only for reference, i.e. they were not endorsed by the WHO).
  - The "scientific" prediction of several thousands dead used the Linear No-Threshold (LNT) model, which is increasingly being identified as incorrect at low dose rates. The LNT model is mostly based on Japanese A-bomb high-dose survivors, which as previously mentioned is apples and oranges.
  - The more-recent scientific data clearly disputes the validity of the LNT model at low dose rates; i.e. these studies have investigated low additional doses (within the annual natural background) have found no negative impacts. Many will actually argue that low doses are beneficial (look up hormesis), but either way the effects are minimal.
- The cancer predictions displayed in the 2006 WHO report have thus far grossly exceeded what has actually happened for the first 30 years.
  - The same prediction methodology that projected the thousands of eventual deaths, also predicted a 375% increase in cancer+leukemia deaths among the liquidators in the first 10 years (190 deaths would occur versus the nominal 40) – this should have been clearly visible in the statistics of this controlled dataset, yet no increase was found.
  - The latency period of solid cancer is decades, so it can still be speculated that a spike will eventually appear, but 30 +years after the accident no increase (certainly not thousands) has been scientifically demonstrated.

Fear of Radiation is Worse than Radiation Itself

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- As horrific as ~40 deaths are, there are thousands of manmade, industrial accidents that have caused more fatalities (google it for yourself).
- In addition, nuclear is proven to be far safer (fewer deaths per energy generated) than any other energy source (cold, oil, natural gas, biofuel, wind, hydro, solar - you can google this too). Why a miniseries? because fear of radiation sells.
- Tell that to the victims of Fukishima; the tsunami killed thousands, but coverage by the media focused on the reactor and radiation harmed no one (except for some casualties caused by the evacuation due to fear of radiation).
- The same affect is evident in the regions surrounding Chernobyl: coverage by the media convinced people their bodies were ticking cancer time bombs and fear of radiation made them leave their homes, with extreme detrimental sociological effects (depression, suicides and abortions).
- Again from the 2006 WHO report “Consensus: The mental health impact of Chernobyl is the largest public health problem caused by the accident to date”; so even for the worst nuclear accident of all time, fear of radiation was worse than the radiation itself.
- Now, HBO has created a show that spreads the irrational fear of radiation to new extremes (I wish the actors that played the scientists weren't so good!) – their highly successful show has misinformed 10s of millions.
- This fear of radiation is holding back humanity, because public/political opposition and the corresponding inflated cost (over regulation) has strongly curtailed the use of nuclear energy.